European Association of Remote Sensing Companies

Sentinels Benefits Study (SeBS)

A Case Study

Navigation through sea-ice in Greenland

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Setting the Scene

Ivaana opened her computer. It was already showing her Facebook page and she clicked through to the ice-group. The latest ice images had already been uploaded and so she opened the one for Ilulissat and sent it to the printer. Once done, she put on her coat and stepped outside into an icy blast. She hurried to their shop, unlocked the door and pinned the chart just inside the entrance to the shop.

Ivaana and Malik ran the traders' shop in Ilulissat. It was a focus for the community, and it was both as a service and as a small attraction for the local people that they pinned the latest maps on the board in the shop.

Johan came by later that morning. "It looks good for Christmas," he said to Malik, "the ice in the sound is holding off-shore and should stay open until Thursday when the Ivalo Arctica is planned to arrive bringing our presents. The kids will be really happy to know that Father Christmas will arrive in time"!

"*Any plans to go hunting*?" asked Malik. "*Sure*", said Johan, "*next week I plan to look for some Caribou, and if the ice off Disko thickens up, I plan to do some fishing as well*". "*How about we go looking for some Minke"*, said Malik, "*we still have one quota left for this year"*. "*Maybe",* replied Johan, "*we should talk with Magnus, he is the whale guy."*

On Thursday, it was Malik who was up first and who printed the day's ice images from Facebook. The picture had changed dramatically overnight, the wind had turned and now the ice was being blown into the entrance to the bay. When Ivaana joined him, he expressed his concern that the RAL ship would not be able to get through. *"The children will be so disappointed if Santa does not arrive before Christmas. Their gifts should be on the ship tomorrow."*

"You worry too much", she said smiling, "*the ship will arrive. Captain Thomas will know how to get through, the satellites will show him the way".*

Sure enough, the following afternoon, just a few hours later than planned, the Ivalo Arctica came steaming in, pulled up beside the short quay and prepared to unload the goods and parcels for the people of Ilulissat.

Santa had arrived.

This is a story to set the scene for the case. It is imaginary but is based on stories which we heard during our research. All characters are fictional and any resemblance to living persons is completely accidental

Executive Summary

Everything about Greenland is affected by ice. As the largest, non-continental island, communities on Greenland are in themselves islands in an inhospitable climate. There are no roads connecting the settlements to each other and all transport is by sea, by air or across the land-fast sea-ice.

All goods coming to the island arrive by the sea-bridge provided by the shipping company Royal Arctic Line (RAL). RAL describe themselves as a "piece of infrastructure" and has a sole-concession to transport goods to and from the port of Alborg in Denmark to Greenland. Without RAL, life on Greenland would be very basic for its 56,000 inhabitants.

RAL ships use the ice-mapping services provided by the Danish Meteorological Institute (DMI) to help navigate through the sea-ice which affects Greenland waters all the year round. The service helps them to avoid waters with high iceberg concentrations and to find the open water through which they can sail more rapidly and more safely. For the last few years, the ice-maps are generated using data coming from the European Copernicus Sentinel satellites.

As well as RAL, the ice services help the local fishing companies Royal Greenland and Polar Seafood to operate more effectively and more safely and other vessels sailing in Greenlandic coastal regions. This enables benefits through cost reduction, better efficiency and better safety. Overall, Greenland is estimated to benefit by between €8.6m and €12.5m each year from the use of Copernicus.

1. Danish Meteorological Institute (DMI) produces daily maps of the ice conditions that help ships navigate through the ice off Greenland.

€800k pa

2. Royal Arctic Line use the maps to avoid the ice off Greenland, they have an exclusive concession for the sea transportation of all cargo to and from Greenland. As a result, the shipping company is Greenland's bridge to the rest of the world.

€2.75-3.65m pa

3. Other sectors depending on shipping such as local fisheries and oil transport save time and fuel and operate more safely.

€560k-1.02m pa

4. Business and the local economy operate more efficiently and safely, stimulating economic growth.

€200k-1m pa

5. Citizens can be sure that the supermarkets and other important shops will be stocked, jobs are assured through reliable navigations so increasing living standards.

€4.31-6.45m pa

Greenland has a large geo-political strategic value which is enhanced by safe effective sea transportation.

total
€8.6m-€12.5m

1 Introduction & Scope

1.1 The Context of this study

The analysis of the *'Navigation through sea-ice in Greenland'* case study is carried out in the context of the 'The Sentinel Economic benefits Study' (SeBS). This 4-year study is looking to develop cases showing how Earth Observation (EO)-derived products based on data generated by one or more Sentinel satellites deliver value to society and citizens. The Sentinel satellites form a crucial part of EU's Copernicus Programme, providing space-based observations on a full, free and open basis. Data coming from the Sentinels – together with other data collected by contributing missions and ground, sea or airborne instruments – is used to support key economic or societal areas such as agriculture, insurance, disaster management, climate change monitoring, etc. Sentinel data are thus a key component of the Copernicus Services, and a crucial source used by companies to deliver products and services helping different users across the Globe.

1.2 What is the Case all about?

Everything about Greenland is affected by ice. As the largest, non-continental island, communities or settlements on Greenland are in themselves islands in an inhospitable climate. There are no roads connecting the settlements to each other and all transport is by sea, by air or across the land-fast sea-ice[1].

All goods coming to the island arrive by the sea-bridge provided by the shipping company Royal Arctic Line (RAL). RAL describe themselves as a "piece of infrastructure" and has a sole-concession to transport goods[2] to and from the port of Alborg in Denmark to Greenland. Without RAL, life on Greenland would be very basic for its 56,000 inhabitants.

Ice is a constant feature of the Greenland landscape. Flying over its territory, there is not much else in view than snow and ice. The temperatures mean that the seas freeze over in winter and in summer, icebergs calve from the active glaciers all around the Greenland coast. Generally, they drift down the east coast and up the west coast[3] posing a real threat to shipping as both the Titanic and the M/s Hans Hedtoft found out to their peril.

Hence navigating through the ice becomes a part of the everyday life. RAL are required to serve all the communities on the island no matter how small they might be. Through experience and word of mouth they know the ice conditions and which routes are open, but the ice conditions change very quickly and sometimes this knowledge is not sufficient to follow the best routes. This has led

[1] Sea-ice that is "fastened" to the coastline. https://en.wikipedia.org/wiki/Fast_ice

[2] All goods except fuel.

[3] A good illustration of iceberg circulation around Greenland can be found at https://www.canada.ca/content/dam/eccc/migration/main/glaces-ice/AEC39A7A-4C8D-4EAE-B2E0-374A8ACE7D6D/driftchart.gif

to an ice-service provided by the Danish Meteorological Institute (DMI) located in Copenhagen which has evolved over the years to use data coming from the Sentinel satellites.

DMI provides a number of ice-products to the people in Greenland. These are used by the captains of RAL ships as well as many other islanders. A Facebook group used to disseminate images has 3000 followers and regular exchange between them. Local fisherman, ferry captains, charter boats, or individuals simply going from one settlement to the next all consult the images before traveling. The local fishing companies which dominate the Greenlandic economy use them as does of course RAL.

The images help save time in moving about and save lives. Without RAL, life on Greenland, if possible, would be very basic. Without the images, RAL operations would be less efficient and more dangerous; facts which extend to every facet of life on the island. This SeBS case seeks to evaluate just how important the DMI ice-mapping services are to the Greenland economy.

1.3 How does this case relate to others?

This is the second SeBS case dealing with sea-ice; the first one[4] was set in the Baltic and addresses the Finnish (and Swedish) economies. How do they compare?

We described Finland as "an island" as 90% of its goods are transported by sea. In the case of Greenland, it really is an island with close to 100% of the goods carried by ships. The RAL is the sole operator with a concession from the Greenlandic government; in the Baltic, one company operates the icebreakers even if many shipping lines are benefiting.

In the Baltic, the objective is to pass through the ice. Icebreakers are used to keep "fairways" open and to guide ships to the ports like Oulu in the north of the Gulf of Bothnia. In Greenland, no ice breakers are used and the objective is for the ships to avoid heavy ice. In extreme cases, the naval vessels operated by the Arctic Command can rescue ships which have become trapped, otherwise the ice-mapping services offered by the DMI are used to circumnavigate heavy sea-ice or sea-ways blocked by ice-bergs or drift ice.

In the Baltic, ships are arriving from all over the world. Some of the vessels have hulls to resist the ice but many have not. The ships' captains are often from warmer climates and have no experience of sailing through ice. Hence, the role of the ice-breaker becomes very important to avoid mishap.

In Greenland, the vessels are constructed to a higher ice-standard and skippers of the RAL are all experienced in sailing through icy waters. Ice-breakers are not deployed and, as we shall see later, are even unwanted by the local population.

The population served in Greenland is only 56,000 people compared to around 1.3m around the Gulf of Bothnia. This makes a difference and the economies are completely different. Consequently,

[4] Sawyer, G. and De Vries, M. "Winter navigation in the Baltics." Copernicus Sentinels' Products Economic Value: A Case Study (2015)

the absolute benefit is much higher in Finland than in Greenland even if the per head benefit is higher in the latter.

1.4 More About the Study

Each case study analysed in SEBS, focuses on products and services which use data coming from Sentinel satellites, measuring the impact of that product or service throughout the value chain. The starting point is the primary user of the satellite data, followed by a step-by-step analysis whereby the operations of beneficiaries in each subsequent link of the value chain are analysed, all the way down to citizens and society.

In this process, the main aim is to understand and demonstrate the value which is generated using satellite-based Earth Observations (EO) and particularly the data coming from the Copernicus Sentinel satellites. Each case study thus underlines the causal relationship between the use of Copernicus Sentinel satellite data and benefits resulting from their use, including increased productivity, more efficient and environmentally-friendly operations, economic gains and improved quality of life, among others. The evaluated and demonstrated benefits can be used:

- By policy makers to justify the investments which have been made into the Copernicus programme,
- By space agencies to demonstrate that the technology for which they have public responsibility is capable of delivering strong, beneficial results,
- By other public agencies which are using EO data and services to meet their operational requirements, e.g. the European Environment Agency (EEA) and European Maritime Safety Agency (EMSA),
- By the European Association of Remote Sensing Companies (EARSC) to promote the capabilities of the industry and the strong benefits which can result from the use of the services its members deliver,
- By companies to promote their capabilities and the power of their products and services.

In the framework of this project, 20 case studies are planned with reports to be published on each one. The study has started in March 2017 and will end in mid-2021.

1.5 Acknowledgements

We wish to thank the following persons for their time spent talking with us to develop the case linked to "*Navigation through Sea-ice in Greenland*". In particular, to Matilde Brandt Kreiner and Anders Bay Larsen who gave us much of the background and introduced us to a number of the experts we have consulted.

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Ole Krarup Leth – Deputy head of R&D and Remote Sensing Group leader, DMI.

Søren E. Olufsen – Head of Ice Services, DMI

Keld Quistgaard – Ice analyst, DMI

Anders Bay Larsen – Director of Fleet Management, Royal Arctic Line

Thomas Christensen – Ship captain, Royal Arctic Line

Anders Olsen – Head of Trawlers, Royal Greenland

Henrik Riisom Hansen – co-owner, Martek Aps.

Helle Siegstad – Head of Department, Greenland Institute of Natural Resources

Thomas Bøggild – Greenland Pilot Service

Rasmus Kimer – Arctic Command

Niels Chemnitz – Head of Logistics, KNI / Polaroil

Torben M Andersen – Professor Economics and Business Economic, Arhus University.

2 Sea-ice and the Greenland Economy

2.1 The Greenland Economy

Greenland is the world's largest island; Antarctica and Australia are considered as continental land-masses. Politically, it is an autonomous region within the Kingdom of Denmark, and not part of the European Union since 1985. In 1979, Denmark guaranteed home rule to Greenland, and more recently in 2008, Greenlanders voted for the Self-Government Act, which transferred more competences from the Danish to the local Greenlandic government.

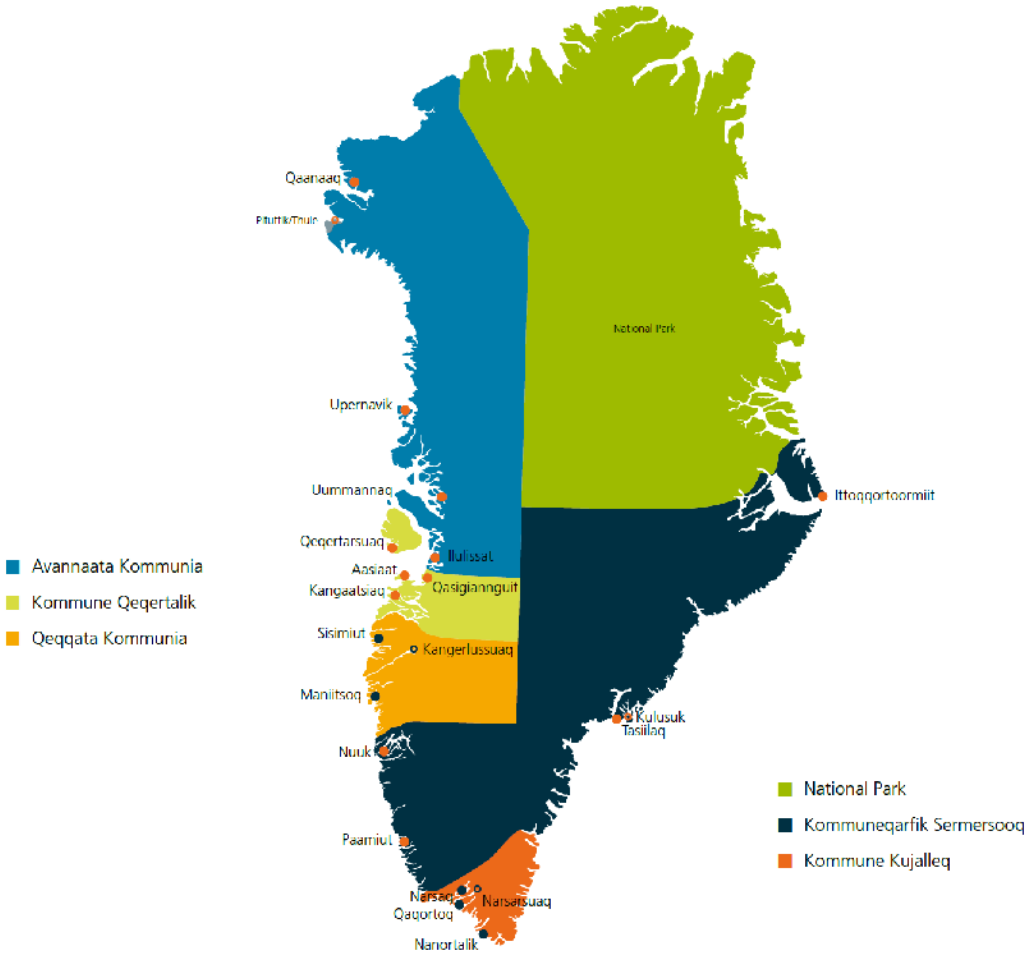

Figure 2-1: Greenland and the major Settlements

Overall, the Greenland economy is quite small with a GDP in 2017 of $2.7 billion (€2.4b) yet the small population means the GDP per head is circa $37,000 (€32,500) placing Greenland on a par with Italy. Despite movements towards stronger political independence, Denmark still provides an annual subsidy of about DKK 3.4 billion (€470 million) to Greenland[5] – some 60 percent of

[5] https://naalakkersuisut.gl/en/About-government-of-greenland/About-Greenland/Economy-and-Industry-in-Greenland

Greenland's annual state budget and close to 20% of the GDP. That Denmark offsets this payment as part of its contribution to NATO and the continued presence of a US air base in Thule to the North of the country, illustrates the crucial geo-strategic role which Greenland plays.

Aside from international politics, we have got to know Greenland as quite an inhospitable island where about 56,000 people are living on an area that is bigger than France, Germany, Spain and the UK combined. Ice invades their shores every year from the north, which may be permanently frozen, to the south where icebergs cause an all-year-round threat. As the inland ice-sheet covers most of the landmass and towns and villages are spread around the coast in Fjords and little islands, virtually all traffic and transport passes via the sea (mainly goods and people) or by air (people, some goods) or over the land-fast sea-ice in the winter. There is no road system connecting the various towns and settlements in Greenland. Thus, sea-ice and icebergs are a major concern for basically the whole population and play a decisive role in the Greenland economy.

This has also great impact on most of Greenland's economic activities that are concentrated within a relatively small radius around its capital Nuuk on the southwest coast. Nuuk has grown rapidly in recent years driven largely by the local population migrating from the small and often isolated villages into the largest town on the island. Even so, the population of Nuuk is “only” around 17,000 which comprises roughly one third of the Greenlandic population.

> *Greenland has a large primary economic sector, due to the predominantly fishing-based economy, some agriculture and a few mining projects. The secondary economic sector is minute and consists almost exclusively of seafood procession and construction businesses. Greenland´s tertiary economic sector is large, consisting primarily of a large public administration, the infrastructural businesses, and a growing tourism industry.*[6]

In 2017, Greenland exported €504M and imported €623M, resulting in a trade deficit of €119M[6]. Fish and processed fish products account for about 90% of its exports with minerals accounting for around 2%. Naturally, this creates a high dependency on fish exports and makes Greenland very vulnerable to worldwide demand and fish prices. While catch volumes had declined some years ago, positive price developments and larger quotas for prawns in recent years have resulted in good revenues in large parts of the fisheries and contributed to a positive GDP growth. This meant that after having contracted in three consecutive years, Greenland's economy has faced steady growth since 2015 largely thanks to rising prices for fish and shellfish.

Developments in the fisheries are directly impacting on the job market with a total workforce of about 25,000 employees. The fishing industry is estimated to employ some 4,500 people whose jobs in turn are linked to global demand for fish. The biggest employer in Greenland however is the public sector with about 10,000 employees.

[6] Greenland in Figures 2018; published by statistics Greenland www.stat.gl/

Figure 2-2: Royal Greenland trawler loading the catch from local fishermen (c) Royal Greenland

Beside the fishing industry, some economic activities such as construction contribute to the Greenlandic GDP, however to a much smaller extent. Whilst activities in connection with extraction of and exploration for raw materials have diminished considerably with two smaller mineral extraction projects having started in 2016 and 2017, investment in building and construction has increased over the last years especially in Nuuk, and further growth is expected in the coming years. At the same time, statistics indicate that private consumption is increasing rapidly. Yet, these developments do not represent adequate solutions and do not compensate for the structural problems such as a very narrow business sector that Greenland faces. The tourism and cruise industry sectors can only slightly offset the small business sector but are considered future strong growth sectors and thus promoted heavily by the government.

Turnover

	2010	2011	2012	2013	2014	2015	2016
	DKK million						
Fishing	995.3	1,092.2	1,273.2	1,217.3	1,505.1	2,000.9	2,265.5
Mining	24.1	55.2	89.3	95.0	45.0	26.9	25.2
Industry	687.4	709.8	589.5	580.9	569.2	472.8	531.7
Construction	2,146.4	2,018.3	2,323.7	1,897.5	1,665.9	1,986.4	2,217.7
Wholesale, retail trade, repair work	7,473.1	8,349.6	8,597.7	8,575.7	8,787.1	9,571.9	10,893.7
Hotels and restaurants	328.5	350.8	338.4	306.0	307.8	339.6	392.8
Transport	2,837.8	3,257.4	3,198.3	3,067.7	3,135.4	3,368.9	3,569.7
Finance and Insurance	336.5	391.5	511.9	503.8	560.0	552.3	564.6
Real estate and business services	1,023.5	1,059.7	983.5	1,049.6	1,065.8	1,060.7	1,074.7

Source: http://bank.stat.gl/ESERESBAL

Table 2-1: Annual turnover of business sectors in Greenland

A crucial actor that keeps the economy running is the Royal Arctic Line (RAL). In interviews, RAL was described as a bridge, without which, Greenland would be disconnected from the world. It has the responsibility to make sure Greenland's imports and exports arrive safely, timely and reliably in Greenland or Denmark respectively. It has the single concession to ship goods (except oil) within, in, and out of the country. They consider themselves as a piece of infrastructure like a bridge. It is not an unrealistic comparison.

2.2 Sea-ice

As mentioned above, ice and especially sea-ice play a crucial and indeed dangerous role in every aspect of life in Greenland. It is estimated that more than three quarters of Greenland is covered by the only permanent ice sheet outside Antarctica. In fact, it is covered by so much ice – at its thickest the ice is over 3km deep – that the central Greenland landmass has subsided over the course of time considerably and lies below sea-level. On top of that, Greenland has innumerable isolated glaciers and small ice caps in its peripheral areas.

Ice encountered in Greenland waters is of two types: sea-ice and icebergs. Sea-ice can further be subdivided into three types: first-year ice (FYI), multi-year ice (MYI) and land-fast ice. Icebergs are masses of freshwater ice derived from glaciers descending from the Greenland Inland ice sheet.

First-year ice, as its name implies is new ice that forms each winter. Multi-year ice is sea-ice that has grown over more than one winter. MYI originate in the Arctic Ocean and drift into Greenland waters through the Fram strait and down the East Greenland coast, and in western Greenland through the narrow Nares strait. East Greenland ice regime is dominated by MYI most of the year, whereas FYI plays a dominant, but seasonal role (from November to June) in Baffin Bay and West Greenland. Land-fast ice (or simply fast-ice) is an unbroken cover of sea-ice that grows from the coast each winter, either formed locally or composed of consolidated drift ice floes. Icebergs are present in all Greenland waters, year-round.

Sea-ice usually starts forming more extensively from November onwards, extending southwards from the Arctic first towards Baffin Bay, and subsequently towards the Davis Strait and Labrador

Sea over the winter reaching its peak in March[7] (see the maps of monthly mean sea ice coverage in Greenland waters in Figure 2-3.

Sea-ice in the Arctic Ocean is pushed southwards by the Transpolar Drift Stream that drives it against northern Greenland and the Canadian Archipelago[3]: the ice compresses and deforms into ridges, leading to the thickest ice in the region; see Figure 2-3.

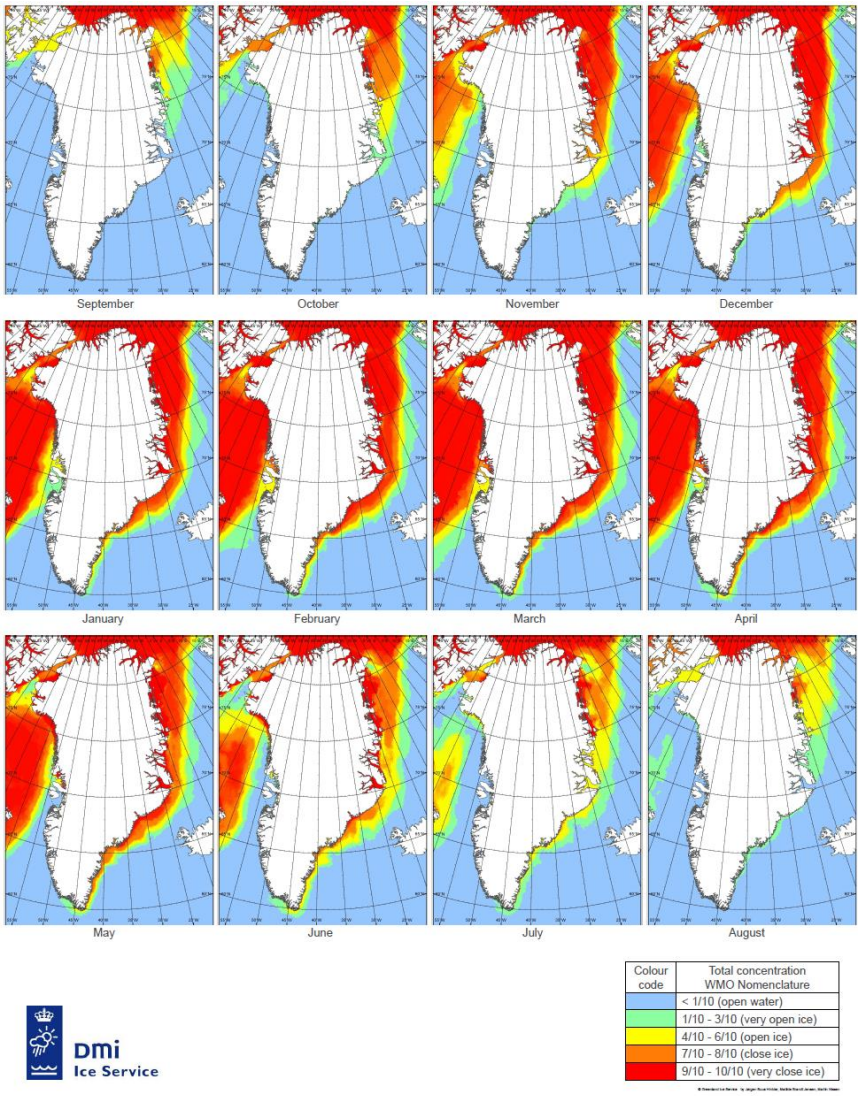

Figure 2-3: Monthly mean (2000-2010) sea-ice concentration

(http://www.dmi.dk/fileadmin/user_upload/havis_og_arktis/fortolkning_af_havis/Poster_MonthlyMeanIceConcentration.pdf).

Sea-ice that forms or becomes trapped in the Beaufort Gyre may circulate around the Arctic for several years. Sea ice that forms or becomes trapped in the Transpolar Drift Stream generally leaves the Arctic more quickly within usually one or two years. Because of this, sea-ice in the Beaufort Sea has more time to grow and reach the thermodynamic equilibrium thickness, so that it becomes

[7] See here an animation of sea-ice extent and developments over the last years: http://polarportal.dk/en/sea-ice-and-icebergs/sea-ice-extent0/

thicker. Due to the circular rotation of sea-ice in the Beaufort Sea, ice floes frequently bump into each other. This also means that ice deformation is common and leads to thicker and more ridged ice compared to other regions[8].

As the ice builds up, moves southward and ultimately spreads eastwards, it is exposed to strong winds, making it **more dynamic and fast-changing as well as difficult to predict** (compared to other regions with heavy sea-ice such as the Baltic which are without any icebergs or such dynamic changes[9]). Because of these harsh and difficult, Greenlandic sea-ice conditions, "**the art of sailing through ice is to avoid the ice**", as Henrik Riisom Hansen from Martek, a private passenger shipping company from Nuuk, put it quite nicely.

Fishing for shrimps takes place mainly in the northern Baffin Bay as the shrimps tend to be much bigger up north, and higher profits can be made. Due to the specific ice conditions, trawlers have to be extremely cautious not to get trapped in the sea-ice that is entering Baffin Bay over the course of winter. Traditionally, the bay has not been navigable most of the year especially in the north-west because of the ice cover and high density of floating ice and icebergs in the open areas. In the last years however, **traffic has steadily increased**. In an average year, RAL would start heading towards the north-western settlements and villages in April when the ice begins to retreat and break open to bring fresh supplies and pick up the local fishermen's catch of the preceding winter.

Figure 2-4: Ship arriving in Ilulissat

That the **waters off Greenland with its sea-ice and icebergs are dangerous** has been demonstrated several times in history. The most dramatic incident off Greenland took place in 1959 when the MS Hans Hedtoft struck an iceberg and sank south of Cape Farewell, southern Greenland[10]. The ship

[8] For more information, see here: https://nsidc.org/cryosphere/seaice/processes/circulation.html.
[9] For more information, see another SeBS case study on ice navigation in the Baltics here: https://earsc-portal.eu/pages/viewpage.action?pageId=35620366
[10] For more information, see here: https://en.wikipedia.org/wiki/MS_Hans_Hedtoft.

was on her maiden voyage with 40 crew and 55 passengers onboard. The ship was carrying several parish registers of great national importance and the tragedy represented a big cultural loss of national history. The most famous ship ever struck by an iceberg is arguably the Titanic which sank in 1912 in the Atlantic and was considered – like the MS Hans Hedtoft – the safest ship of its time. It is assumed today that the Titanic **collided with an iceberg that originated from the Jakobshavn (Ilulissat) Glacier** in West Greenland. Naturally, because many Greenlandic families lost a relative in the sinking of the MS Hans Hedtoft, the accident plays a more important role in Greenland history. It forms part of the collective memory of the country and has shaped national identity until now, as expressed in some interviews. The loss of Hedtoft also led directly to the founding of the Ice Patrol in Narsarsuaq, South Greenland; as described later in the report.

Still nowadays, **even with the advancements in technology and the latest support services such as Earth observation, ships get trapped and stuck in sea-ice**. The latest incident off Greenland took place in March 2018 when the Arctic Umiaq Line passenger ship Sarfaq Ittuk had been surprised by changing winds and thus got stuck in fast-moving sea-ice in Torssukatak in southern Greenland for about a week – it had missed the open non-frozen sea by only a few 100 meters[11]. The incident demonstrates the uncertainties resulting from navigating off Greenland and the related risk that can never be fully excluded.

2.3 Working and Living in Greenland

Greenland´s population lives almost exclusively in towns, settlements, sheep farms and weather stations at the coast. About 50 percent live in the five largest towns Nuuk, Sisimiut, Ilulissat, Aasiaat and Qaqortoq which are all located in the southwest. About 90% of the population is of Greenlandic ancestry. The remaining 10% are predominantly Danish, although it has become increasingly international recently[12]. When we went to Nuuk and had our various interviews, we noticed that a majority of high-level positions are occupied by Danes, indicating the still existing quality gap in education between Greenland and Denmark. This has improved, but still remains a challenge despite efforts to transport teachers via boats or maintain costly little schools even in smaller villages.

The main economic hub is Nuuk where one third of the population lives. While Greenland has suffered from net emigration for more than 40 years, Nuuk has benefited from internal migration, mainly from outer villages and settlements to towns such as Nuuk. It is a quickly developing town with a net gain of 4,000 people since 2000, an increase by about 30%. This boom was very visible during our visit where we saw numerous construction sites. Two new distinct town quarters have been built in addition to the old town, which were built in two waves in the 1990s and early 2000s respectively. This internal migration to Nuuk has also made the construction business the second biggest private sector employer in Greenland. Here again, the sector is dependent on imports of raw materials for the buildings and thus on a reliable provision of goods through RAL from Europe.

[11] "Greenland: Passenger Ship Stuck in Ice" in The Maritime Executive, last retrieved 9th November 2018.
[12] For more information, see here: http://www.stat.gl/publ/kl/GF/2018/pdf/Greenland%20in%20Figures%202018.pdf.

Figure 2-5 Ilulissat Harbour (Tripadvisor)

Outside the 5 major towns, life certainly comes with a number of hardships given the rough and bleak climate. In the settlements and villages which make up about 50% of the population with an average of 100 to 300 inhabitants, **the main source of income comes from fishing**. From the accounts of the interviewees, fishery is a very profitable though hard job in Greenland and more than 20% of the total workforce makes their living with it, making higher revenues than an average civil servant. These so-called dinghy fishermen work throughout the year as long as the ice (and quotas) allow for it. Their catch, whether processed or not, is picked up by the bigger ships of RAL or Royal Greenland who subsequently export it to Europe and other global destinations. However, the high revenues are contrasted with expensive imported goods that are not produced in Greenland with its narrow business sector.

Education, healthcare and power generation are free of charge. Should villagers for instance be in need of medical treatment, private passenger companies such as Martek transport doctors to the settlements or bring them to the next medical facilities which is paid for by the state. The dispersion of villages over such a wide area of land is also problematic for instance for the maintenance of power stations and generators or other technical equipment so that private passenger companies often have to transport specialists of various professions to the villages. Interestingly, in order to accelerate legal proceedings and avoid lengthy and costly transports to the next regular court house, police boats often have “courts” onboard.

2.4 Everything Depends on Ice

As we have seen, every aspect of life and work is somehow dependent on ice both onshore and offshore. Ice in winter can make the whole cities and sea-based traffic come to a halt. Especially with regards to fishing, the big trawlers from Royal Greenland and Polar Seafood cannot put to sea whereas fishermen from the villages can at least continue ice fishing through sea ice. When the sea-ice reaches the southern tip of Greenland from the west, even the ports of the 5 biggest towns cannot be called at. This complicates the service provided by RAL as a bridge between Greenland and Europe: they have to weigh up between keeping a reliable flow of goods between Greenland and Europe on the one hand and the risk of getting trapped in sea-ice or struck by icebergs on the other hand. Moreover, ice glaciers are covering most of the Greenland land mass and inhibit substantial land-based travel between towns.

Dog sledges have been used traditionally for hunting, fishing and transportation on the land-fast ice, and are still used when sea-ice inhibits the passage of ships. However, dog sledges provide local transport and cannot compensate for the capacity which ships can provide. As such**, ice disrupts heavily the local economy and stops much of the traffic** especially during winter times. In cases of emergency, locals have to rely on (costly) helicopters. This also means that villagers usually get their last goods and supplies just before Christmas when the ports are just open still. Once ports are frozen, the villagers have to await March or April depending on the latitude and the specific ice conditions. In the interviews, we have heard that climate change does not have that big impact (yet) on the time period when ports are open or frozen especially in the north-western settlements.

Although the Greenlandic climate has indeed been changing over the last two decades, the still icy climate has yet prevented the business sector from prospering more intensively. With agriculture only a limited option in the south[13], Greenland is a country with limited accessible resources. The ice has hampered a proper exploitation of natural resources which most likely include gold, zinc, anorthosite, ruby, uranium, rare earths as well as oil and gas among others. Some mines had been opened over the last 15 years but turned out not to be profitable and thus closed again shortly after. It has to be noted that opening Greenland to mining and the exploitation of natural resources has been a controversial and at times divisive topic among Greenlanders. Whilst some think it could make Greenland more independent from fish exports and Danish subsidies and grow the private business sector, others rightfully fear for the preservation of nature and untouched landscapes.

Despite all the involved challenges and hardships that ice implicates in Greenland, Greenlanders have started more recently to see the ice as an opportunity. (Sustainable eco-) tourism is being fostered and promoted especially close to the glaciers for hiking and heliskiing among others. The government also seeks to attract the cruise industry for stops in Greenland on their way to Canada to enjoy the view of the ice and glaciers. However, as we heard in interviews, nobody can (yet) live solely on tourism, especially in Nuuk.

[13] "Tomatoes, peppers, strawberries in Greenland's Arctic valleys" in Reuters, last retrieved 8th November 2018,

2.5 Climate and Environmental Considerations

Whilst Greenland potentially has one of the biggest impacts on climate change, it is also one of the few countries which considers it will benefit from climate change. The melting of the Greenland ice sheet would cause sea-levels to rise by 7m; a catastrophic outcome for the world if it arrives. On the other hand, a retreat of the ice-sheet and less sea-ice would open up the possibility of extracting, currently-inaccessible minerals or increasing tourism. In this case, we are more concerned to look at the latter, ie the impact of climate change on the Greenland economy and society from more modest changes and especially rising temperatures and we are leaving aside the contribution made to climate change research and understanding coming from the use of the Sentinel data. It is a different topic.

The Polar Portal[14] reports that "*Unusual weather resulted in an atypical melting season in the Arctic. The 2017-18 season in the Arctic has once again been extraordinary. A cold summer with high levels of precipitation has benefitted the Ice Sheet, whilst glaciers have continued the development seen during the last six years in which they have more-or-less maintained their area. The sea ice, on the other hand, has been more vulnerable, with high sea temperatures and warm winds leading to a large area north of Greenland being ice-free in two separate periods – February and August respectively.*"

There is clear evidence that the Arctic sea-ice is thinning and especially the summer sea-ice extent has diminished. Monitoring of Arctic sea ice from satellite observations over the last ~40 years show a clear positive trend in the length of the open-water season around all of Greenland apart from the very North, though with large local variations within especially the last 10-15 years. Figure **2-6** shows the trend in open water days for the Arctic and around Greenland.

We heard several times about the interest of Chinese companies to open mining operations in Greenland. There is also Russian interest to open-up new shipping routes[15]. Increasing open water shows the reducing levels of sea-ice. The exceptional open water to the North of Greenland in 2018 coincided with a trial voyage conducted in Summer 2018[16]. This was conducted by two companies; Ironbank (Canadian) and China Non-Ferrous Mining Corporation to enter the Citronen fjord. The trial was successful leading to claims that the mine would now be feasible. However, as we saw from the quote above, 2018 was exceptional in terms of open-water to the NW of Greenland and there would still seem to be the need for more sustained clear waters or business models incorporating heavier sea-ice operations probably using ice-breakers.

[14] Polar Portal: Monitoring ice and climate in the Arctic. http://polarportal.dk/en/news/2018-season-report/

[15] https://www.arctictoday.com/novatek-teams-chinese-partner-arctic-shipping/

[16] https://www.arctictoday.com/shipping-northern-greenlandic-mine-feasible-owner-says/

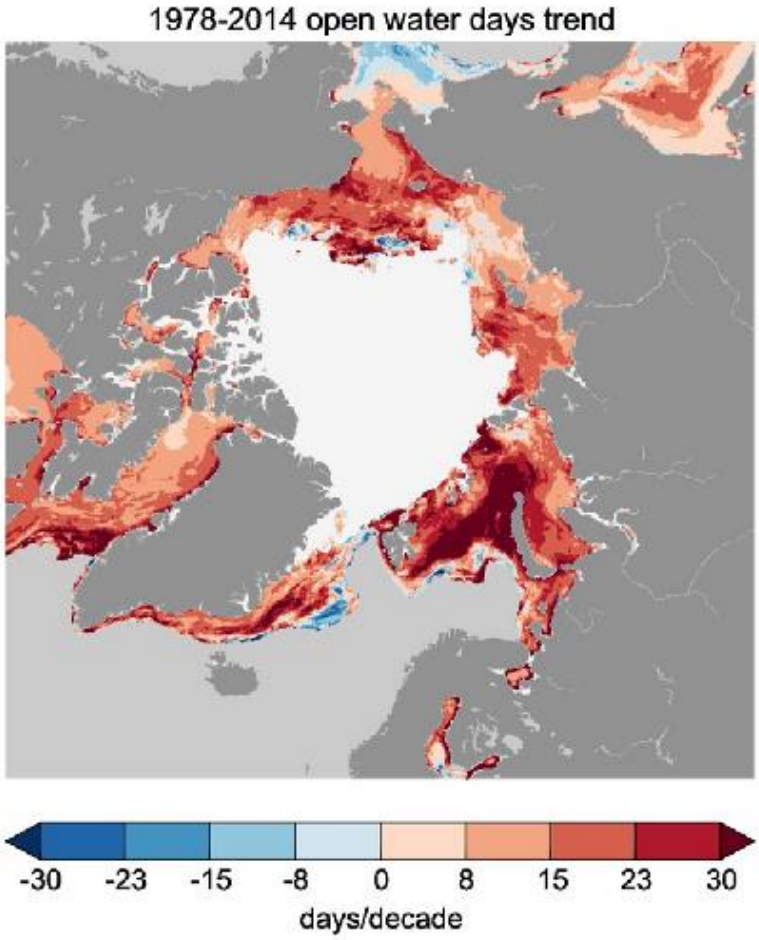

Figure 2-6: Open water days trend for the Arctic[17]

Figure **2**-**7** shows the temperature at 80 degrees latitude through 2018 in comparison to the mean temperature from 1958 to 2002.

The rising temperature are causing a shorter ice-season with consequent impacts on Greenlandic life. The shrinking ice cover is shown in Figure 2-10 where the total area of sea-ice for the last 4 years can be seen to be 1m square kilometres less than the mean value 1981-2000 i.e 15% less. This represents a critical difference for the Greenlandic people.

[17] This map shows the trend in the number of days of open waters, calculated across the periods 1978-2014. The number of days of open waters for a given point is defined as the interval between the sea ice concentration falling from greater than 30% to less than, and remaining so for at least 5 days, until the ice concentration again climbs to above 30%, and stays so for at least 5 days.

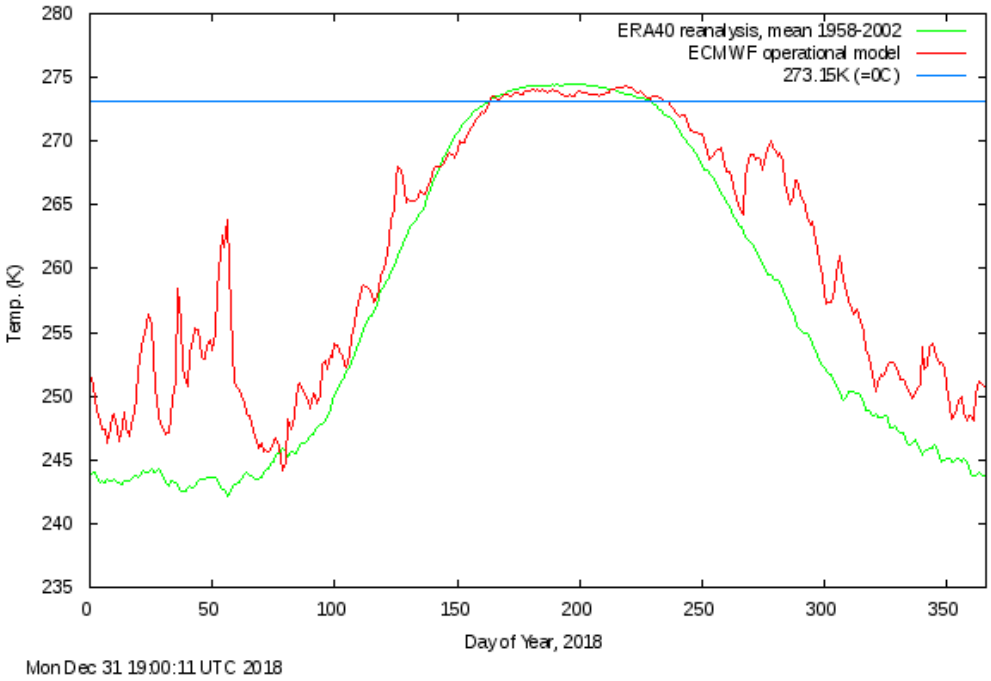

Figure 2-7: Daily mean temperatures at 80th Latitude. Source: DMI.

In Northwest Greenland the land-fast ice extent has reduced a lot since the 1970s affecting the traditional living of the hunters in the local settlement of Qaanaaq (see figure and picture below).

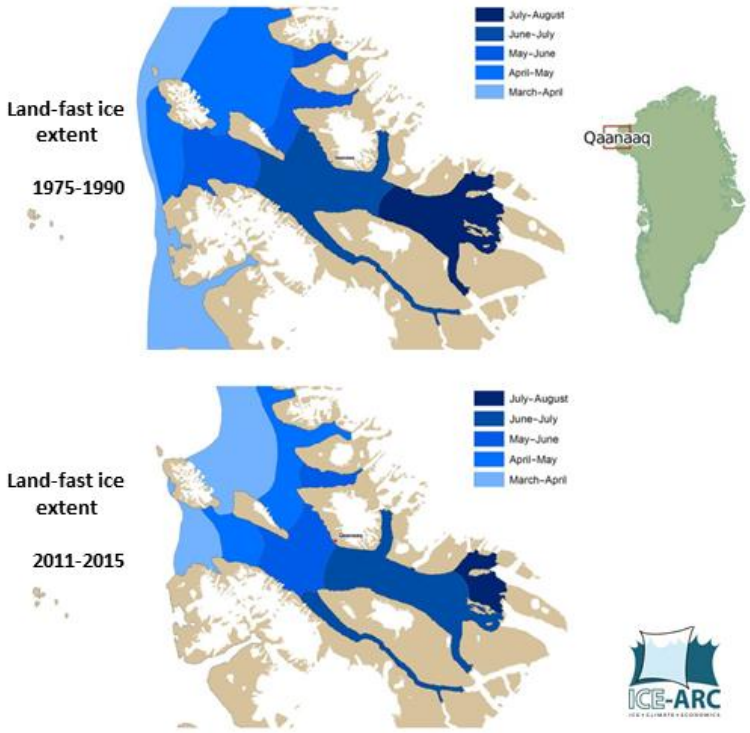

Figure 2-8: Changes in land-fast ice extent in Northwest Greenland between 1975-1990 and 2011-2015, based on observations in Landsat imagery (EU Ice-Arc project).

Figure 2-9: Dog-sledges and hunters on broken land-fast ice that has broken up outside the settlement Qaanaaq in Northwest Greenland, July 2018. Picture taken by Hans Jensen (www.hotelqaanaaq.dk).

The consequences will be felt in different ways:

- Seas may be opened up with a shorter ice-season but this does not necessarily mean they are safer. Increased calving of ice bergs from the ice sheet and glaciers will still bind up fjords and threaten ships sailing close to the shores[18].

  ships sailing in the area report about an increased formation of drift ice as a consequence of the warmer climate. This amplifies the risks associated with shipping in the region and has the potential of making some areas less accessible,

- Fishing will be affected by changing fish stocks with shrimp moving further north into colder waters and reducing in the south in warming waters which will encourage cod and similar species. These feed on shrimp accentuating the reduction in stocks to the south.

  Climate change is likely to affect shrimp fishery and to lead to a decline in the total amount of shrimp in Greenlandic waters. This is in part because of an increase in sea temperatures and in part because those same temperature increases are expected to boost the occurrence of cod, which feed on shrimp[19].

[18] http://climategreenland.gl/en/citizen/climate-adaptation/maritime-transport/
[19] http://climategreenland.gl/en/weather-climate-and-the-atmosphere/fisheries/

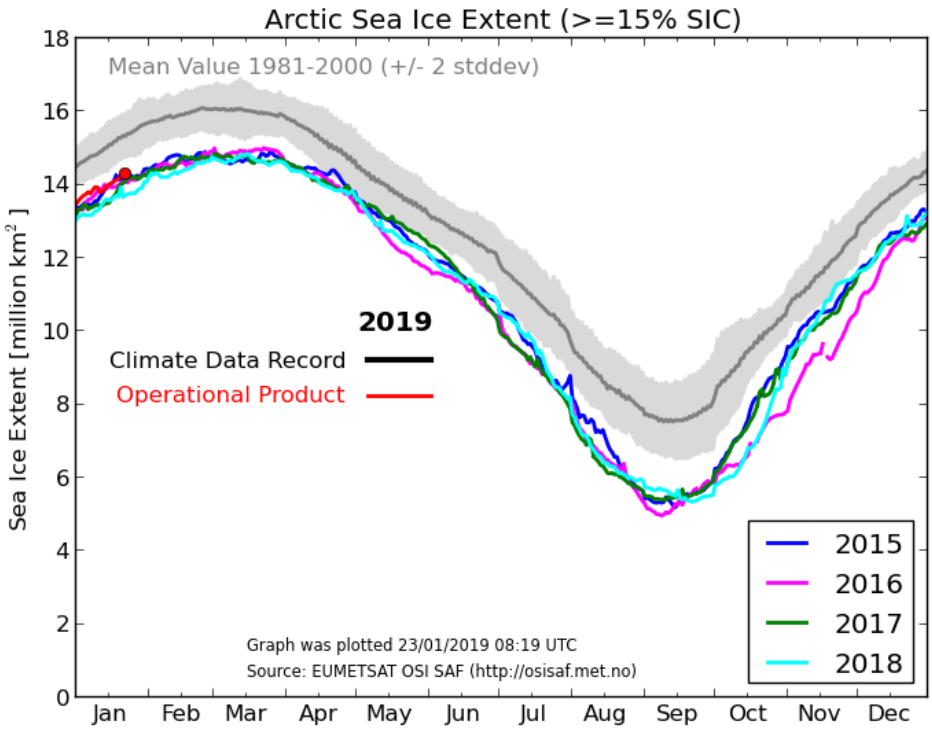

Figure 2-10: Area of sea-ice in the Arctic.

- Hunting is severely affected with a shorter ice-season - but also be social trends in Greenland. As it becomes more difficult to access the prey, the population reduces its dependence on it as a form of living. The younger generation are turning to other interests such as digital occupations often leaving Greenland to pursue them.

> *But in the far north, climate change is hastening the decline of hunting. "The traditional way of life is very challenged," said Bjarne "Ababsi" Lyberth, a biologist and hunting expert for the Association of Fishers and Hunters[20]. People "used to go hunting for weeks on the sea ice. They would go so far out they couldn't see any land. Now they can travel only for one day by sea ice, there's too much open water and it's unstable."*

This is re-enforced by the story from a travel journal[21]

> *"Life as a hunter is getting harder as the changing climate means that warm currents are now coming into the fjord," explained Karl as we perched on low fabric stools. "I first went hunting, aged eight, with my father. We took guns and a harpoon and*

[20] Association of fishers and hunters in Greenland - KNAPK
[21] https://www.wanderlust.co.uk/content/the-future-of-greenland/

travelled across the ice by dogsled. But now the seals and polar bear stay further away – there's less fjord ice in the region." As he spoke, I noticed his face had been etched by a lifetime of sea salt, Arctic winds and long winters.

"When I see young people hanging around and doing nothing it makes me sad," added Karl, sucking on his pipe. "That's why I decided not to teach my son to be a hunter but wanted him to get an education. "Today," he sighed, "he's in Denmark, working with computers."

- Tourism is likely to increase as cruise liners can move further north and access fjords.

  The country has registered a rise in the number of visitors in recent years and with branding of Greenland as Pioneering Nation the aspiration is to increase the inflow of tourists even more[22].

  The Ice Fjord offers exactly what many tourists are curious to experience – an awe-inspiring impression of what nature has to offer. The many great icebergs and the awareness that the speed of change is accelerating at a rapid rate add to the image of an Arctic in transformation – despite the fact that a more complex reality often hides behind.

[22] http://climategreenland.gl/en/citizen/climate-adaptation/tourism/

3 The Ice-Mapping Services

3.1 General Introduction

Sea ice and icebergs are major hazards that can damage ships or vessels transporting passengers, oil, natural gas or goods. Hence the goal in the waters around Greenland is to avoid both hazards. Unlike the situation in the Baltic[23] where icebreakers are used to cut passages or clearways through the ice so making it easier for the passage of ships, in Greenland the goal is to provide information to help the ships avoid the hazards presented.

The main problem in Greenland comes from icebergs calving from glaciers to the north of Greenland and Canada which drift down the coast into the North Atlantic around Cape Farewell. Sea-ice is transported from the Arctic Ocean into Greenland waters through the Fram and Nares straits. Sea-ice also forms locally in the sea and fjords and is blown into narrow straits so blocking them. Winds and currents move the sea-ice and the icebergs around so causing additional problems for accessing the ports, even those deep into fjords. Indeed, which routes are open and when is one of the key pieces of information from the ice-mapping services sought by the ship's captain.

3.2 How do satellites map and monitor sea-ice?

Many different types of satellite data are used for ice-monitoring but essentially, they almost all fall under 2 categories; radar or optical imagery. Other sources also usable for sea-ice monitoring, though with coarser resolution, are thermal infrared satellite data (eg. AVHRR) and microwave radiometers (eg. AMSR2) and altimeters may be used for scientific purposes to investigate ice thickness and for information related to climate change. These sensors have capabilities within sea-ice monitoring that are complementary to that from radar and optical imagery, eg. on ice thickness and ice types. Nevertheless, this case rests almost entirely on the use of radar images coming from Sentinel 1 and other radar satellites such as Cosmo-Skymed, Radarsat and TerraSAR.

Radar imagery can be taken under any meteorological condition as, unlike optical imagery, a radar can "see through" clouds. The imagery is less familiar and much harder to interpret than that coming from optical satellites but performs well to highlight where there is ice and also its nature. Multi-year ice and ridges can be distinguished in Synthetic Aperture Radar (SAR) images as can icebergs. The huge advantage of radar imagery is its day/night, all-weather imaging capability.

Optical images are more readily understood than those from SAR as they are like a photograph but cannot operate through clouds – which is around 70% of the time in the Arctic. Hence if conditions are not good, images which are collected show only clouds. In practice, most images contain some clear areas and some clouds. Sentinel 2 imagery is now being used for the ice-mapping services when areas of interest are visible. A comparison of radar and optical images is given in Figure 3-1 and Figure 3-2.

[23] Copernicus Economics Benefits Study: Winter Navigation in the Baltic; EARSC study Sept. 2015.

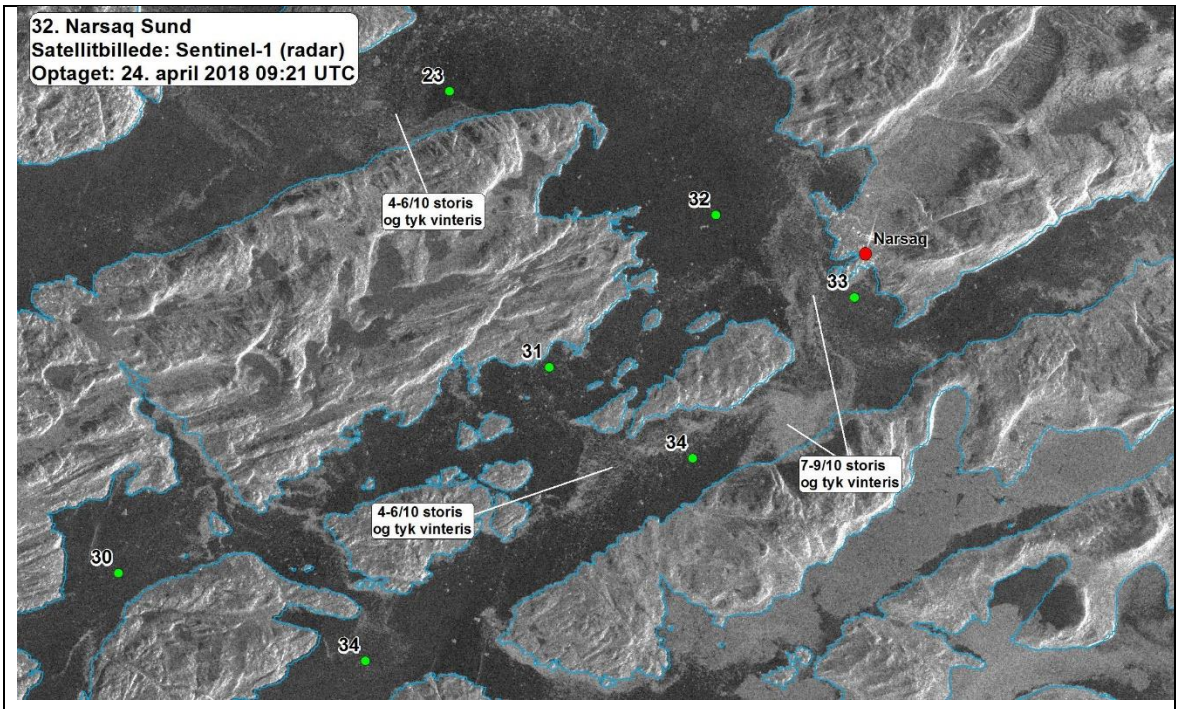

Figure 3-1: SAR (Sentinel-1) Quick-look Image of Narsaq Sound, with sea-ice annotation by DMI. Image contains Copernicus Sentinel data (2018).

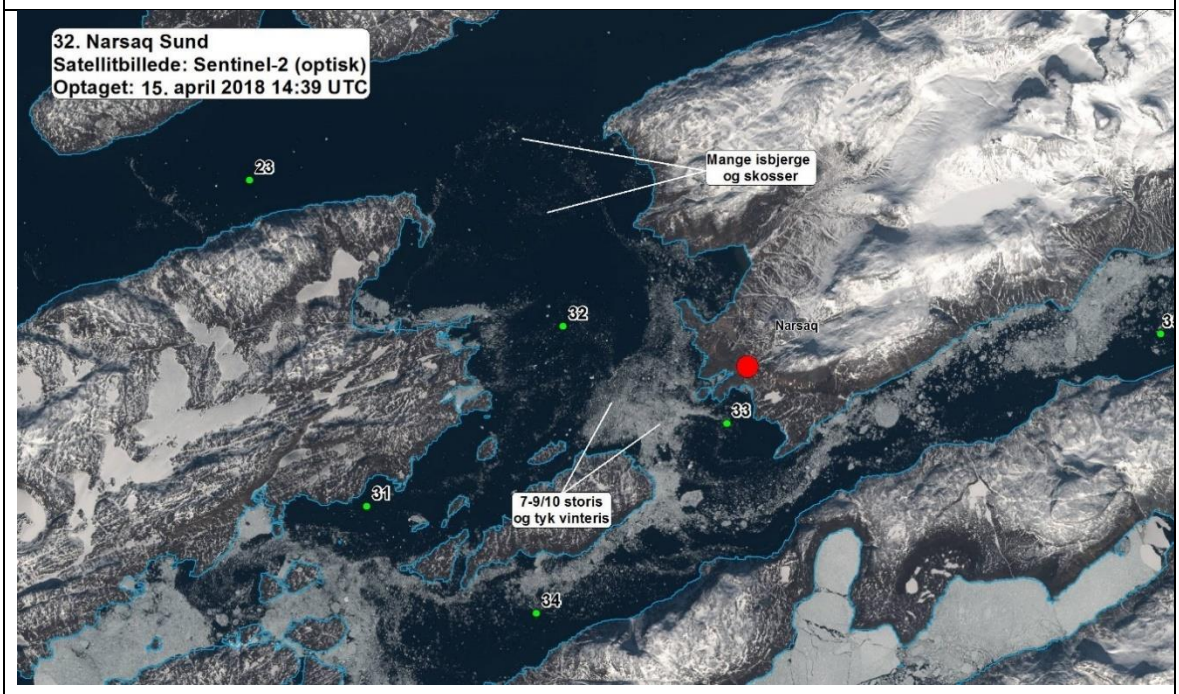

Figure 3-2: Optical Image (Sentinel-2) of Narsaq Sound, with sea-ice annotation by DMI. Image contains Copernicus Sentinel data (2018).

Whilst satellite technologies give the possibility to monitor for sea ice and icebergs and measure for instance its thickness, its spatial extent, its motion and ridges mostly the satellite imagery is

used to detect the ice presence. Skilful ice-analysts are then able to interpret the imagery to identify where the ice is thick and represents a hazard to shipping. This information is important to know to manage operations in hazardous sea-ice conditions. How do satellite images compare with other methods?

Satellite imagery provides wide area, synoptic pictures of the ice conditions. Since the scale of ice fields is quite large, mainly moderate resolutions are fine down to around 10m in scale. Multispectral imagery can provide more information on ice-type but in the main, SAR imagery is used due to its all-weather and day/night capability.

The data collected can be more effective than in-situ measurements due to a higher and faster coverage of a whole area. Constant monitoring is most important to identify the risk and opportunities (for instance in opening shipping lanes).

A key challenge lies in dealing with the latency associated with the satellite imagery, ie the time from when the satellite passes over to when it is delivered to the user. The locations of the sea-ice in the image reflects the situation at the time of acquisition but this might have changed by the time the image is delivered to the users.

A second challenge lies in the interpretation of the imagery. Radar imagery is not so simple to interpret and can on occasions be misleading due to ambiguities induced by e.g. weather and high winds. Therefore, there is a challenge in ensuring that the imagery is used safely and effectively, by personnel who have appropriate training and experience.

Despite this, as we saw in the Baltic and is the case in Greenland, non-experts are using SAR imagery with a good degree of accuracy as they have the real local conditions – “outside their window” - as ground truth which is highly important to interpretation.

3.3 The Greenland Ice-Mapping Services

The DMI Ice-Mapping Service has traditionally had its focus on South Greenland and covers the area with detailed inshore and offshore ice information 2-3 times a week. This is due both to historical reasons; the loss of M/S Hans Hedtoft and the location of the Ice Patrol, and the fact that South Greenland is where many ships enter Greenland waters. The area is dominated by bad weather from the passing of low-pressure systems, resulting in often very dynamic ice conditions. The Ice Service delivers regional and overview ice information for the remaining part of Greenland 1-2 times a week, depending on the ice season. The Ice Service ice analysts are available to the users for advice and information within office hours.

The ice-services provided by the DMI over Greenland take the form of 5 different products:

(a) An overview ice chart over the whole of Greenland.

The ice chart is prepared by an analyst two times each week; on Monday and Thursday. It is a classical ice-chart in that it uses the symbols agreed by the World Meteorological Organisation (WMO); see https://www.dmi.dk/en/hav/groenland-og-arktis/iskort/1258/#c8790.

It is constructed using all available Sentinel imagery as well as imagery from other satellite instruments (AVHRR, MODIS, AMSR-2, etc.) that has been acquired in the previous three days. These ice charts are distributed to users as JPEG's and PDFs from www.dmi.dk and www.ocean.dmi.dk and in NetCDF through the Copernicus Marine Environment Monitoring Service (CMEMS). The overview portal (www.ocean.dmi.dk) is shown in Figure 3-3 and an example overview ice-chart is shown in Figure 3-4.

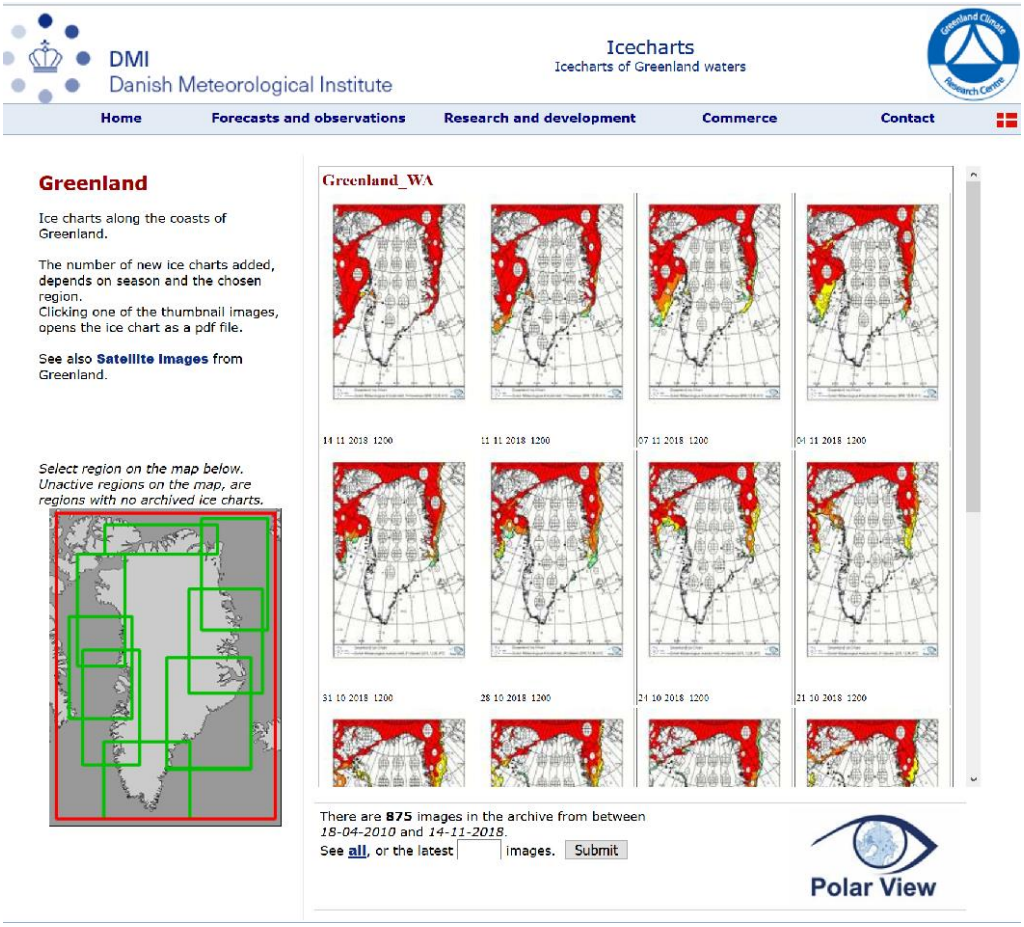

Figure 3-3: The DMI Ice-services portal for ice-charts (www.ocean.dmi.dk).

(b) Regional ice-chart

Figure **3-5** shows an example of a regional ice chart made manually by the ice analysts from one or more Sentinel-1 scenes, and Sentinel-2 imagery if available (and cloud free). Imagery from the US MODIS instrument is also used which should eventually be replaced by Sentinel-3 imagery. The frequency (1-3 times a week) and coverage (Eastern, Western and/or Southern Greenland) of these regional ice charts depend on the ice season and shipping in the area. It is produced and distributed to users as soon as possible after image acquisition, preferably within 6 hours. These ice charts are distributed to users as JPG's and PDF's from www.dmi.dk and www.ocean.dmi.dk and in NetCDF through CMEMS.

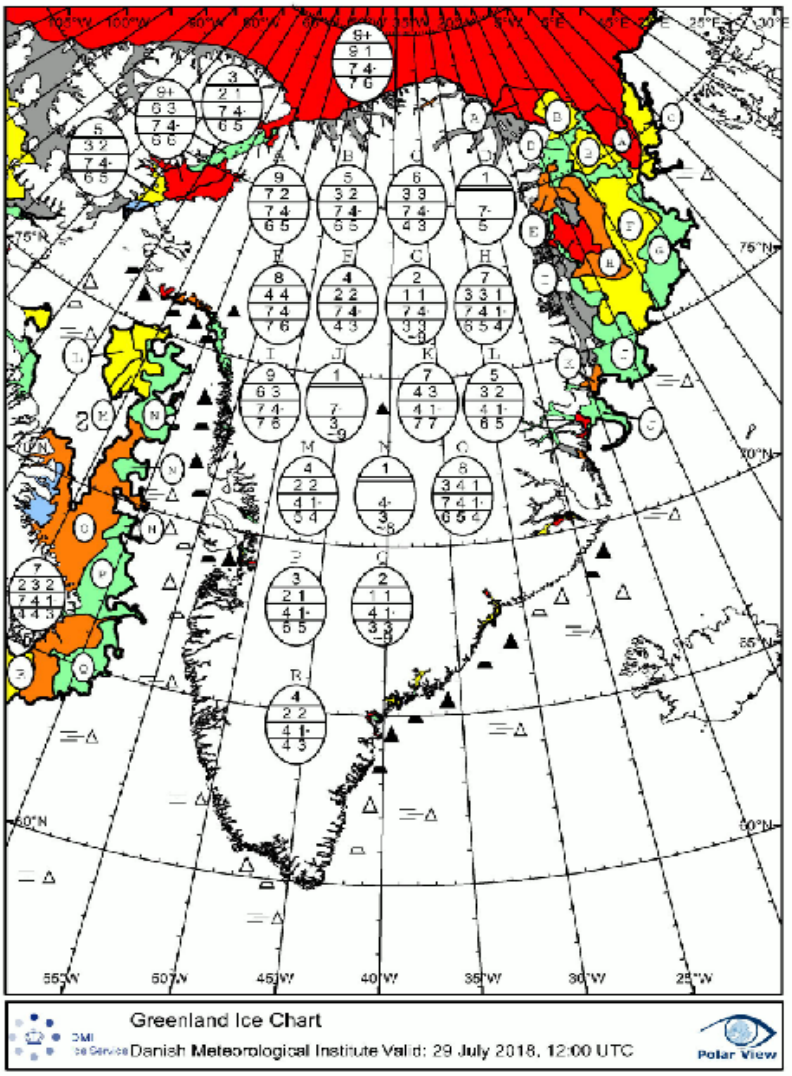

Figure 3-4: An example ice-chart

(c) Iceberg map

Figure 3-6 shows an example of an iceberg map for the waters around Cape Farewell. It is generated using an automated target analysis (CFAR algorithm) of all Sentinel-1 imagery acquired for the Greenland Waters. This product is distributed to users (in different spatial and temporal coverage) in NetCDF through CMEMS and as PNG's from www.polarportal.org.

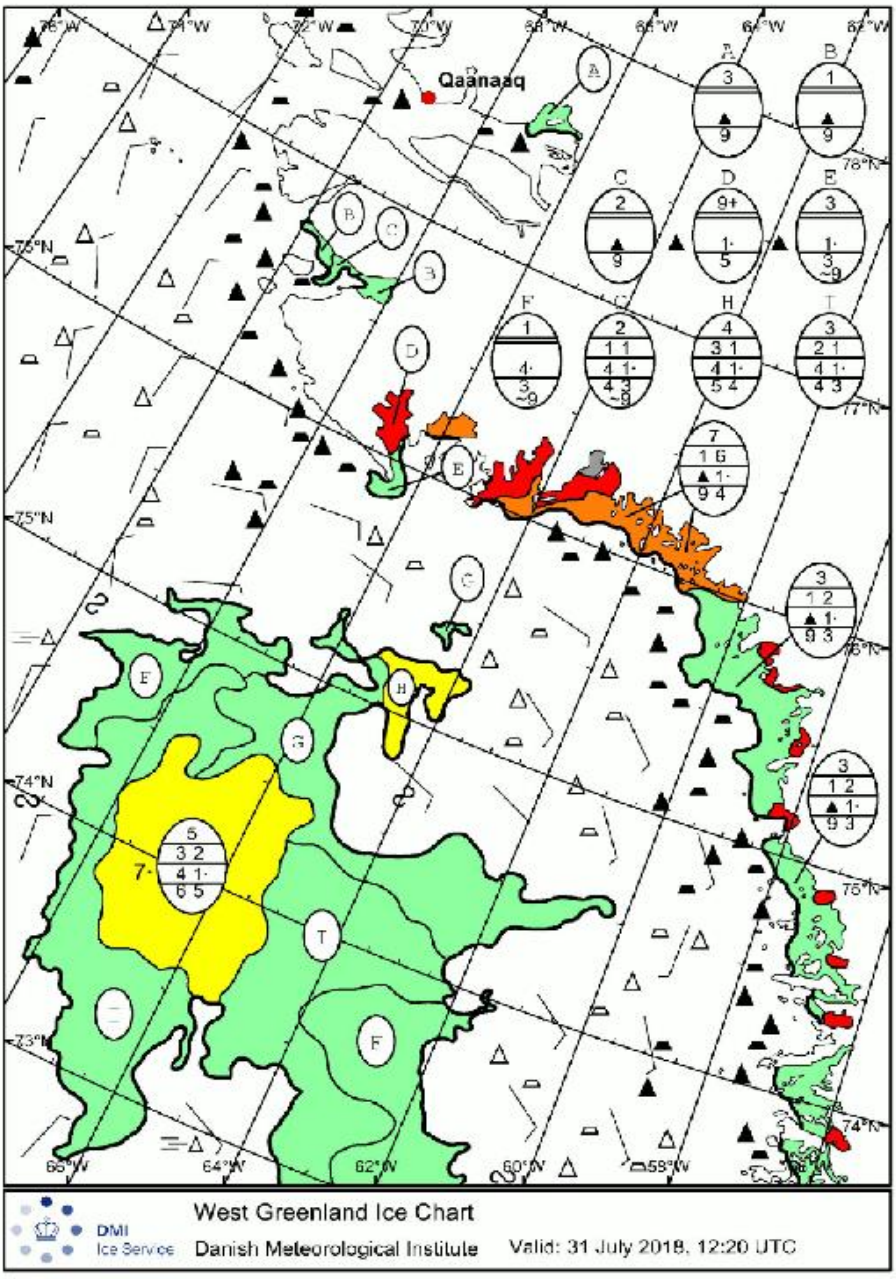

Figure 3-5: West Greenland ice chart from 31st July 2018.

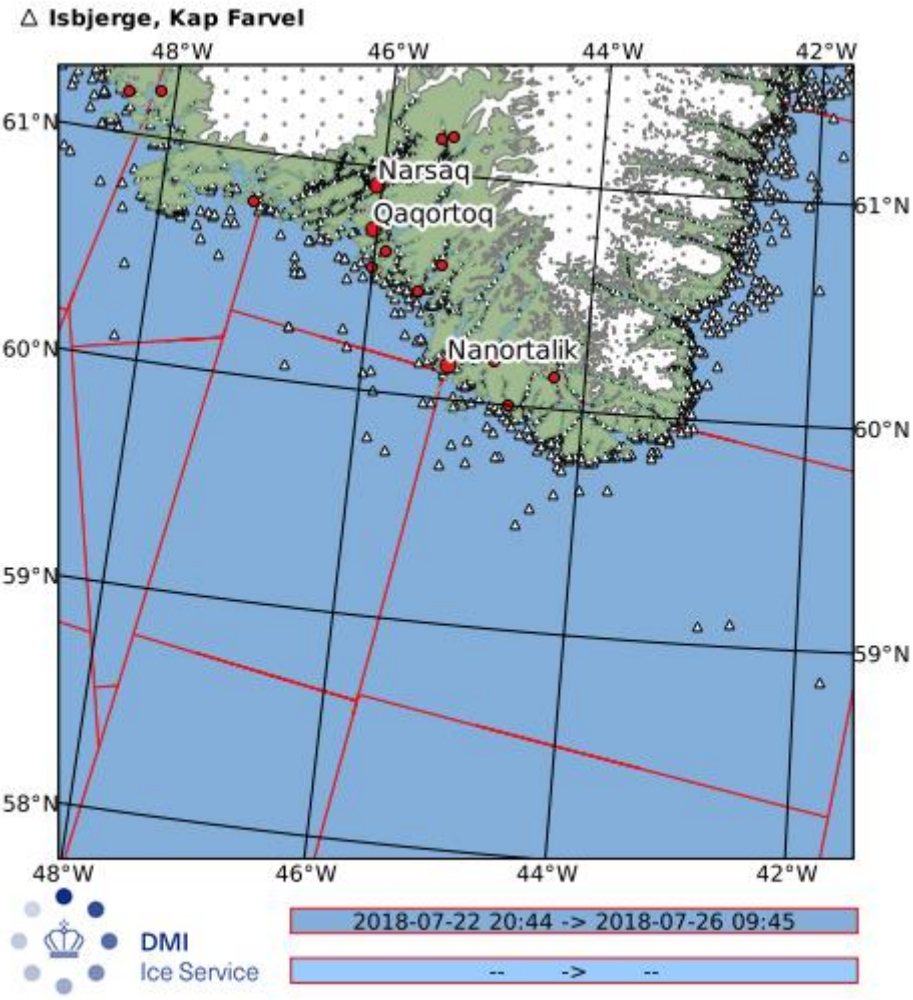

Figure 3-6: Iceberg map for Southern Greenland

(d) A Quick-look satellite image.

Figure 3-7 shows an example of an automated 'satellite image quick-look' that is made from Sentinel-1 images, Sentinel-2 images (and other satellite imagery) for subset areas along the Greenland coast. See: http://ocean.dmi.dk/arctic/satimg.uk.php. This automated service is very popular with especially the Greenlandic users (local population, hunters, fishermen) because the file size is low and fits bandwidth in Greenland and offshore.

The 300m-resampled product that DMI use for these Quick-looks is a daily Sentinel-1 mosaic produced by DTU Space and available from www.seaice.dk. The resampling reduces the file-size and makes transmission easier. The capability to zoom into an area to see details is clearly reduced, but the quick-look provides a useful view for navigators in the area. In addition to these automated satellite image quick looks, the ice analysts also produce image quick looks with sea-ice information annotations - called Annotated Quick Looks (with descriptions, an ice edge line etc.) when necessary or as supplement to the Ice State Bulletin; see examples in Figure 3-1 and Figure 3-2.

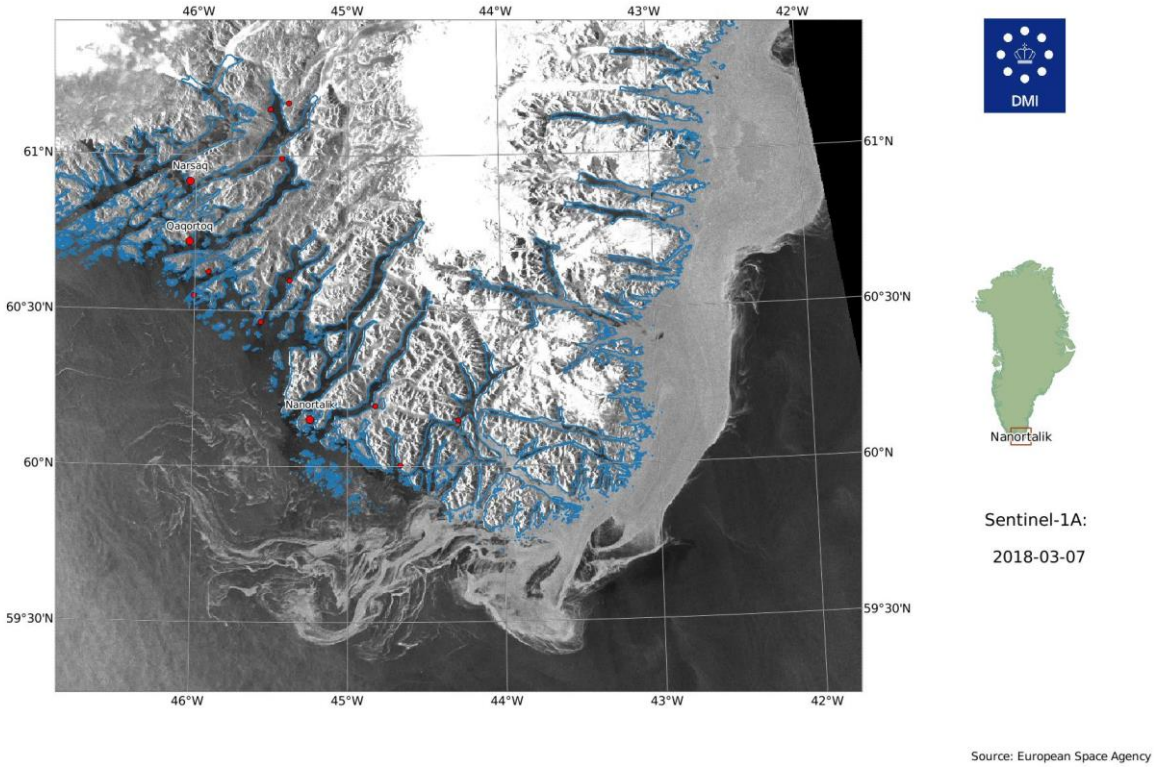

Figure 3-7: Quick-look SAR image for Southern Greenland

(e) An Ice State Bulletin

Until recently, a helicopter was used to monitor 89 critical points along the inshore shipping routes in Southern Greenland. This has now been replaced by the use of the satellite imagery; mainly Sentinel-1. An analyst interprets the imagery to create a short report covering the 89 points of interest which is then sent to users in the region. An extract of the ice bulletin is given in Table 3-1.

Danish Bulletin	English translation
På satellitdata optaget 23. april 2018 20:45 UTC for strækningen Tornarssuk Løb til Sermerunerit, blev følgende isforekomster observeret:	On satellite data valid April 23 2018 20:45 UTC covering the area from Tornarssuk passage to Sermerunerit, the following ice was observed:
01. I Tornarssuk Løb: Enkelte isbjerge og skosser. 02. I Isaløb: Enkelte isbjerge og skosser.	01. In Tornarssuk passage: Few icebergs and growlers. 02. In Isaløb: Few icebergs and growlers.

03. I ruten Isaløb - Arsuk: Enkelte isbjerge og skosser.	03. In the route Isaløb to Arsuk: Few icebergs and growlers.
04. I Isberg Sund: Enkelte isbjerge og skosser.	04. In Isberg Sound: Few icebergs and growlers.
05. I Sønderløb: Enkelte isbjerge og skosser.	05. In Sønderløb: Few icebergs and growlers.
06. I Arsuk fjord: Enkelte isbjerge og skosser.	06. In Arsuk fjord: Few icebergs and growlers.
07. I Simpson Passage: Enkelte isbjerge og skosser.	07. In Simpson Passage: Few icebergs and growlers
08. I Kobberminebugt: Enkelte isbjerge og skosser.	08. In Copper Mine Bay: Few icebergs and growlers.
09. I ruterne Kobberminebugt - Torssukatak: Spredte isbjerge og skosser.	09. In the route from Cobber Mine Bay to Torssukatak: Scattered icebergs and growlers.
10. I ruten inden om Thorstein Islænder: Revler og bælter af 5-6/10 storis og tyk vinteris i den sydlige del af ruten, ellers mange isbjerge og skosser.	10. In the route around Thorstein Islænder: Patches and belts of 5-6/10 Old Ice and thick First-year ice in the southern part of the route, otherwise many icebergs and growlers.

Table 3-1: Ice Bulletin for 12th April 2018

3.4 Delivery of the Services

It is one thing to generate the highly useful products in Copenhagen, but the users are located throughout Greenland! How are the services delivered to its users?

The DMI Ice Service claim a ''*diverse scope of users, with diverse user needs and diverse means of communications*.'' Two web-portals (www.dmi.dk, http://ocean.dmi.dk/arctic/satimg.uk.php) provide an on-line pull service i.e. users can go there and search for then download the ice charts and/or satellite image quick looks which they seek. This works well for the generalized services and an example for the ice-charts is shown in Figure 3-3. A similar service is available for the quick look images; see Figure **3-8**. Users can select which satellite imagery they are seeking for all the regions around the Greenland coast. For example, the quick-look image in Figure 3-7 is accessed in this way.

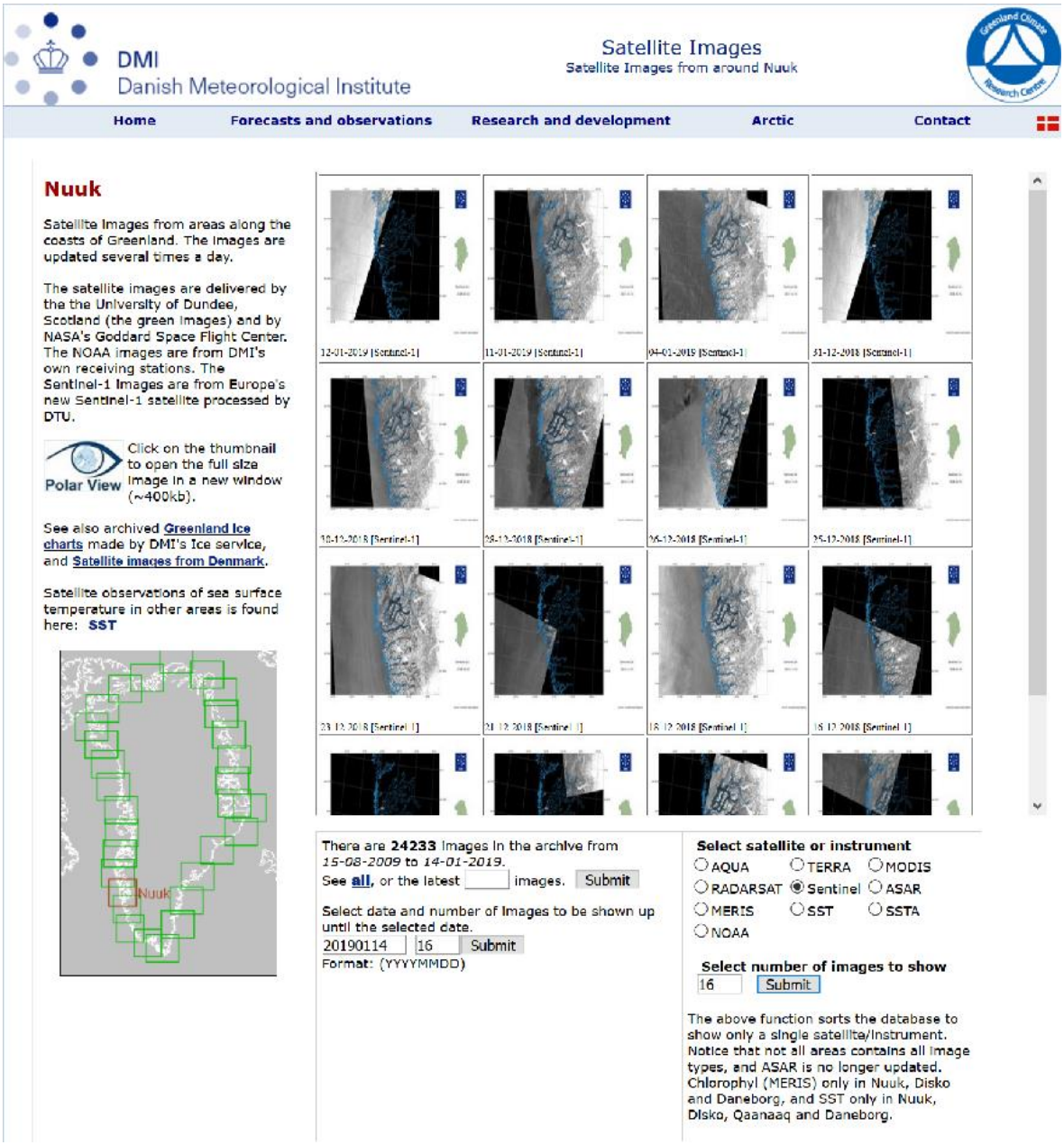

Figure 3-8: Quick-look Image Portal[24]

Higher resolution images are too large to be distributed in this way and a dropbox account was set up whereby privileged users could go to find what they are looking for. But this is a cumbersome way and is not so much used except by a few professional users such as RAL and the Greenland Pilot Service.

The most used way to access the products is surprisingly through Facebook. Facebook is used extensively by Greenland local communities and in that way, the Ice Service has brought the ice

24 http://ocean.dmi.dk/arctic/nuuk.uk.php

services to where the users are. A dedicated group has been set up with over 3000 members. Annotated quick-look images are up-loaded to the Facebook page where they can be accessed. The main advantage is the image compression algorithm used by Facebook which seems to be particularly effective. The page also allows the members to exchange additional information much as was done by radio in the 20th century! It also provides DMI with direct feedback from users of the images.

3.5 The Role of Sentinels and other Satellites

As has been discussed earlier, both Sentinel-1 and Sentinel-2 data are used for the ice-services. Sentinel-1 today is the backbone of the DMI ice services and the Copernicus Pogramme, with its operational satellite missions, has been a game-changer for the DMI Ice Service by the vast amount of complementary and high-resolution radar and optical satellite imagery that is freely available.

The current Sentinel-1 acquisition cycle (using Sentinel-1A and Sentinel-1B) provides daily images over Northern Greenland and images every 2 to 3 days over Southern Greenland but still leaves a 4 day gap every 6 days. This is filled by imagery from the German TerraSAR-X satellite system operating in a wide-swath mode (ScanSAR) and supplied through a commercial contract with Kongsberg Satellite Services (K-SAT) in Norway. In this respect, Sentinel-1 works with TerraSAR-X in a constellation and they complement each other for in-shore mapping purposes. In the critical seasons, this means between 2 and 5 TerraSAR-X images are obtained every 6 days. Imagery from TerraSAR-X, downloaded at the Norwegian ground station in Tromsø by K-SAT, is available to DMI within 20 to 120 minutes from the download depending on the satellite overpass.

Further radar images over South Greenland are taken from the Italian Cosmo-Skymed satellites and the Canadian Radarsat-2 satellite. These are provided by ESA via the portal to the data warehouse (https://spacedata.copernicus.eu) funded by the European Commission as contributing missions to the Copernicus programme and available to the DMI ice service as a result of DMI being a service provider in the Copernicus Marine Environment Monitoring Service (CMEMS).

Sentinel-2 imagery is also used when possible and the OLCI sensor images from Sentinel-3 have a huge potential for the ice services as a substitute to the very useful, but aging MODIS satellites. But until now, the Sentinel-3 OLCI data has been sparsely used by the Ice Service.

Other sources also used for sea-ice monitoring, though with coarser resolution, are thermal infrared satellite data (eg. NOAA- and METOP-AVHRR) and microwave radiometers (eg. AMSR2). These sensors have capabilities within sea-ice monitoring that are complementary to that from radar and optical imagery, eg. on ice thickness and ice types.

3.6 Future Evolution

The consistent request from the users whom we talked with was for more timely information. Ice charts are today made manually by the ice analysts, which is a labour-intensive and time-consuming process, that introduces a time-delay and subjectivity factor to the ice products. The largest future

challenge of the DMI Ice Service is to automize all or part of this manual process to make ice services more efficient and able to utilize the vast amount of Sentinel-data that is available and to be able to deliver faster ice services to the users. This will release some of the Ice-Service staffs' time, that can then be spend on advising users and making even more value-added services. The ice service needs to be more efficient, since its user group is also growing as the Arctic sea ice is thinning and retreating, enabling marine access to a wider area.

Most importantly and ultimately, the users need ice forecasts for safe navigation and planning. And future automatized, detailed and standardized ice observations from satellite data is needed for model assimilation, so that the Ice Service can provide users with reliable forecasts.

DMI work with the Technical University of Denmark (DTU) to solve this, by using artificial intelligence to combine different satellite data with complimentary capabilities, imitating and learning from the manual ice charting process. The methodology is multi-sensor data fusion of Sentinel-1 data and microwave radiometer data from the experimental AMSR2_satellite. DMI collaborate with other national meteorological institutes' Ice Services and service providers in the Copernicus Marine Environmental Monitoring Service (CMEMS) within this field.

Through their involvement as a service provider in the Copernicus Services (C3S and CMEMS), DMI state their needs for future Sentinel satellite missions to EU and ESA[25]. Three of the proposed polar Sentinel candidate missions would be useful for ice services; the L-band SAR mission, the microwave radiometer mission and the topographic mission. The L-band SAR mission (ROSE-L) would be useful for ice monitoring if in close constellation (less than one minute) with a next-generation Sentinel-1 C-band SAR. That will enable automation of the ice analysis.

A possible future with two SAR missions, both C- and L-band, will put even higher demand for automation and more efficient method for producing ice information.

For the DMI aim of developing automated Sentinel-1 based ice-services, the main future gap is the need for an operational passive microwave radiometer mission, such as the Copernicus Imaging Microwave Radiometer (CIMR) Sentinel candidate mission, to work in combination with a next-generation Sentinel-1.

[25] https://www.copernicus.eu/sites/default/files/2018-10/Copernicus-Ex-Ante-Final-Report_0_0.pdf

4 The Use of Satellite Data along the Value-Chain

4.1 The Value Chain for the use of Ice-Mapping Services in Greenland

The overall value-chain is shown in Figure 4-1. In this case, there are many direct users of the ice-mapping services and the value chain is unusual compared to previous cases, for the fact that the fisheries companies appear both as consumers of the service and as beneficiaries of the use by the primary user.

We have seen that Greenland has a low and sparsely distributed population and yet is highly strategic to Denmark. This is reflected in the value chain where many of the actors are government-owned. Since life in Greenland is hard, the government interest to maintain a quality of life and even to see growth in the GNP per person pervades the value-chain.

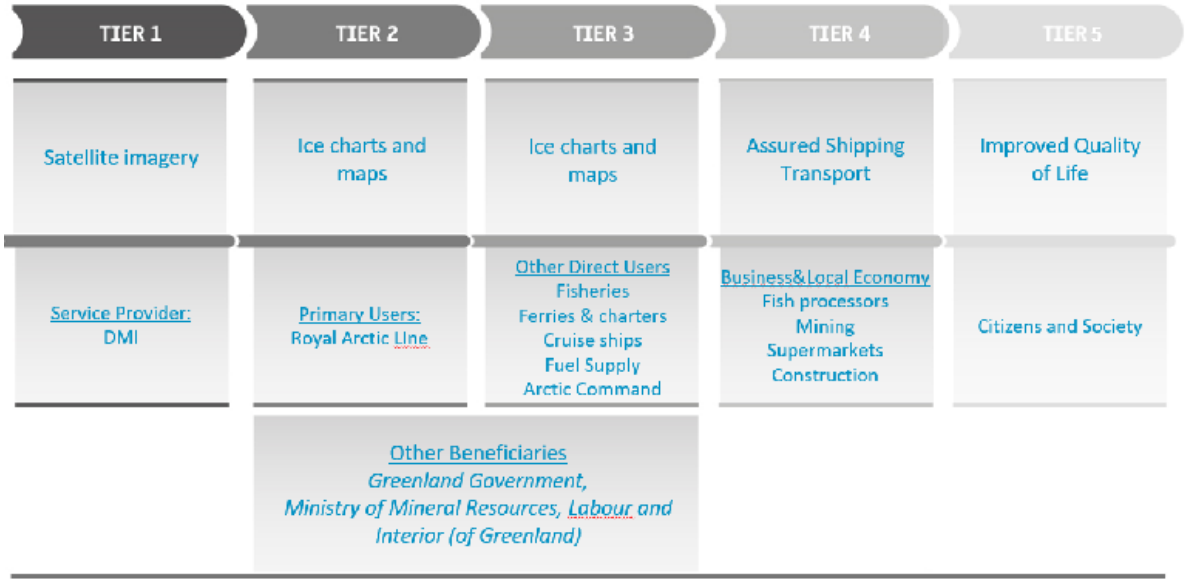

Figure 4-1: Value Chain for the use of the Ice-Services in Greenland, with value characteristic (above).

Since everything in Greenland is dependent on RAL, even if other groups are direct users of the ice-mapping services, RAL is designated as the primary users with the other direct users in their own tier.

4.2 The Actors

4.2.1 Tier 1: Service Provider - The Danish Meteorological Institute

The Danish Meteorological Institute (DMI) provides meteorological services in Denmark, the Faroe Islands, Greenland, and surrounding waters and airspace. Meteorological services include

forecasting and warnings and monitoring of weather, climate and related environmental conditions in the atmosphere, on land and at sea.

The DMI is an institution under the Danish Ministry of Energy, Utilities and Climate, employing 240 people with an annual budget of approx. 300 million Danish Kroners (€40m).

Shortly after the establishment of the DMI in 1872, the institute began to collect information about the occurrence of ice in Greenland waters; the captains of Greenland ships were asked to record their observations of ice on maps that were send to DMI and published as monthly overview ice charts of ice extent. This approach was maintained and only interrupted by the war years 1940-1945. Observations from the ships were supplemented by observations from Greenlandic towns and settlements.

After the end of the war, the number of weather stations in Greenland was greatly expanded, and ice was observed and reported on a daily basis. The observations were supplemented with regular measurements of its thickness in permanent locations. Since February 1950, ice reports from land stations, ships and aircrafts were gathered in a daily telegraphic ice report, which could be intercepted by ships. This also formed the basis for wider sailing planning in Greenland waters.

Figure 4-2: Location of Narsarsuaq Airbase

After the tragic loss of the passenger ship M/S Hans Hedtoft south of Cape Farvel (Farewell) on January 30, 1959, where all 95 passengers died, the Ministry of Greenland investigated the feasibility of shipping all year to and from Greenland as well as a security and rescue service in Greenland. The report, which was available on September 2, 1959, proposed, among other things, the establishment of a permanent ice patrol service based on the abandoned American military airfield in Narsarsuaq in South Greenland (see Figure 4-2).

The first ice reconnaissance by airplane from Narsarsuaq and the inauguration of the ice patrol service took place on November 30, 1959. Since then, ice reconnaissance was done 1-3 times a week covering southern Greenland inshore waters and fjords. First by airplane and twin-otter and later by helicopter. The service ended in November 2017, when DMI decided to switch to utilizing satellite imagery from the Copernicus programme and other sources.

Figure 4-3: Sentinel 2 optical image of the ex-ice-monitoring centre in Narsarsuaq.

Figure 4-3 is a Sentinel 2 image of Narsarsuaq taken in April 2016. It shows the fjords and the sea-ice (with the traces of several ships' passages) very clearly in relation to the ex-ice-monitoring centre (the long, straight runway is visible in the upper centre of the image) whilst Figure 4-4 shows the terrain and the location near Cape Farewell – the southernmost point in Greenland. The centre was operated by 4 staff in shifts - captains from the RAL - as well as pilots for the helicopter which was flown to monitor the ice conditions. The staff from the centre were transferred to other operational positions; 3 were re-employed on board the RAL ships or as ice pilots, whilst a 4th ice-analyst moved to Copenhagen to work in the DMI.

The helicopter flew 1-3 times per week around the area. The timing of flights was adapted to the RAL ships when going to South Greenland ports, and the schedule of the weekly passenger ferry operated by the Arctic Umiaq Line; a wholly owned subsidiary of the RAL. The helicopter was used to take photographs of the sensitive points - 89 in total – at the entrance to settlements or the fjords which gave access, or critical points of passage which are vulnerable to being blocked by ice.

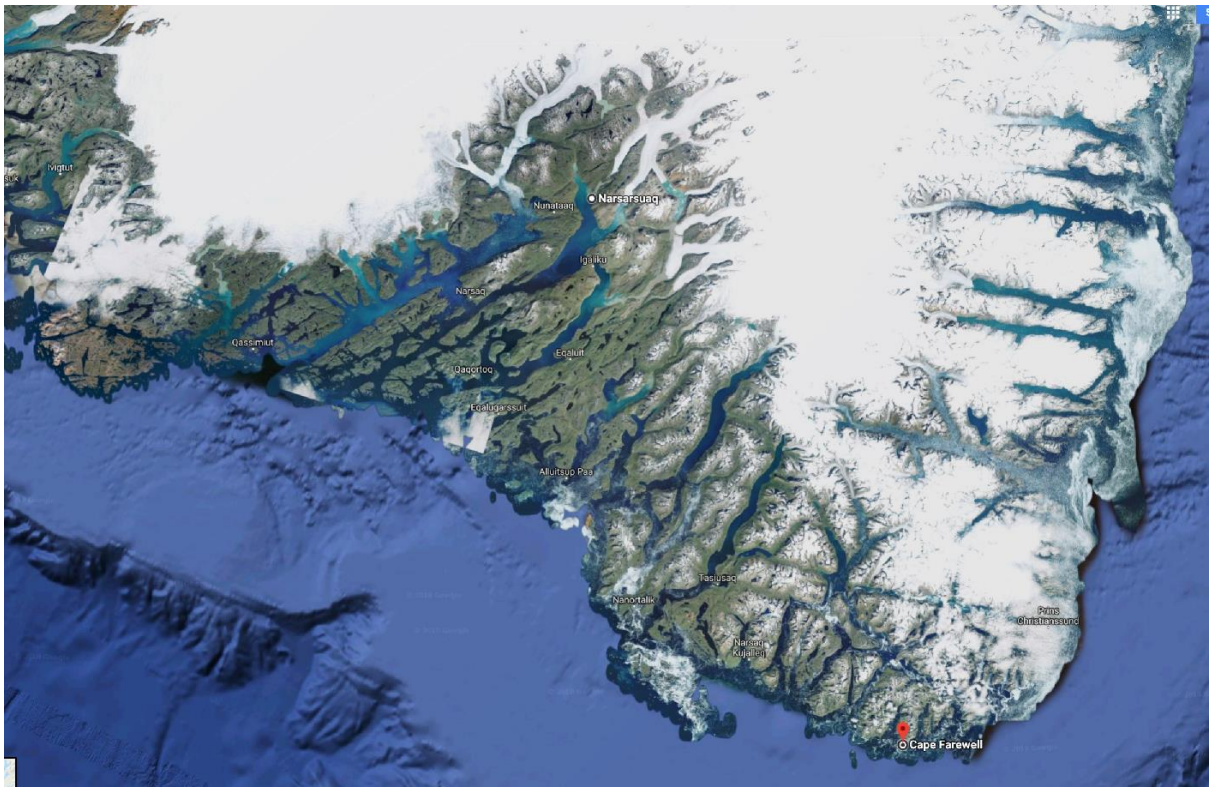

Figure 4-4: Terrain and location of Narsarsuaq in relation to Cape Farewell.

Since November 2017, the service is entirely operated from Copenhagen using satellite imagery and a team of analysts. During the winter when conditions are more stable, the team comprises 3 analysts, but this increases to 6 in the summer when the number of users is higher and icebergs become a more prevalent problem and the sea-ice edge is moving in the northern area of Greenland in Baffin Bay.

4.2.2 Tier 2: Primary User - The Royal Arctic Line

The Royal Arctic Line (RAL)[26] is the primary shipping line supplying Greenland. It was awarded an exclusive concession by the Greenlandic government in 1993 when the company was formed. The company is fully-owned by the government of Greenland.

All goods entering, leaving or transported within Greenland are shipped by the RAL, with the exception of petroleum which is transported by Polar Oil and people being transported by the Arctic Umiaq line (see 4.2.3 b), by private boats or by cruise liners in the case of tourists. RAL operates between Aalborg in Denmark and Greenland with additional goods especially from USA and Canada, being shipped through Reykjavik. RAL operates 13 ports in Greenland.

[26] http://www.royalarcticline.com/about-us/the-royal-arctic-group/

Along with the concession come obligations to ensure that every community in Greenland is served with conditions on frequency of supply as well as its security. Due to the high dependency and the integration into community life, the population of Greenland are completely dependent on the shipping line to import and export their goods.

In 2017, RAL operated a fleet of 11 vessels as illustrated in Figure 4-5; but this is currently being updated and modernized. The fleet consists of larger ocean-going vessels which make the transfers between Greenland and Aalborg and 6 smaller vessels – "settlement ships" which transport goods within Greenland.

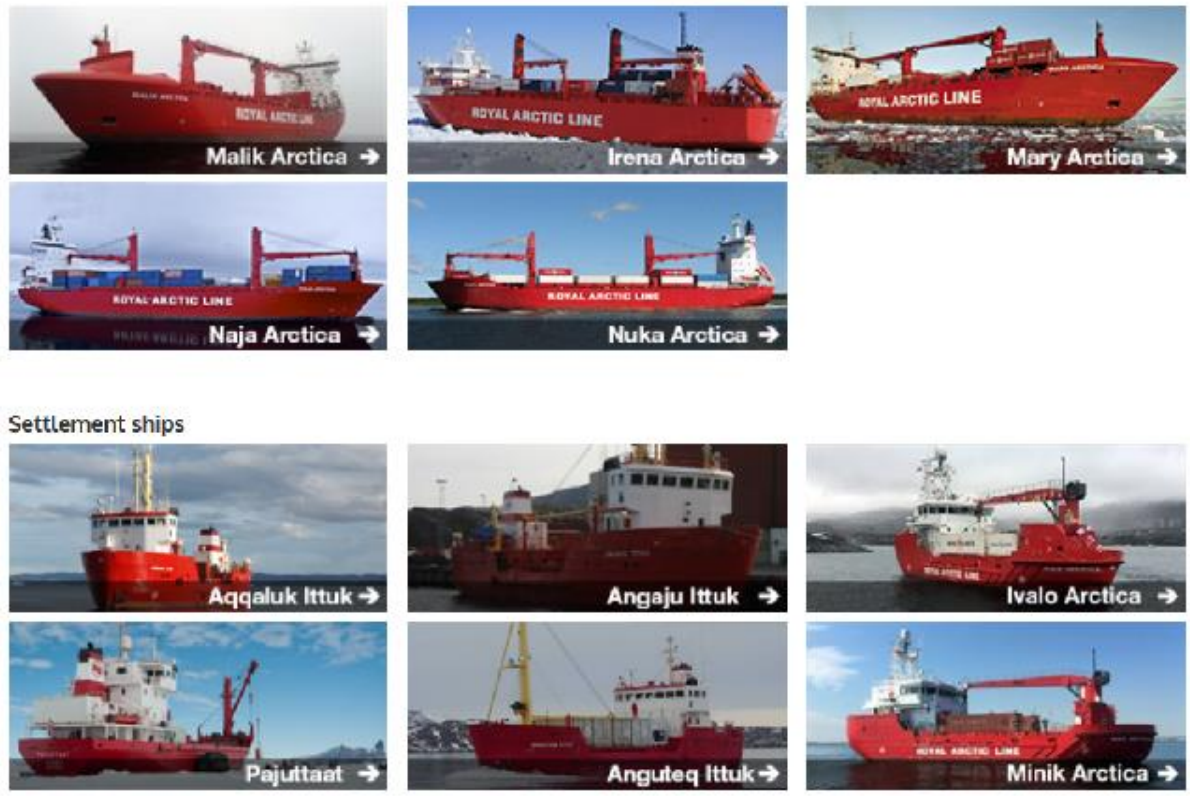

Figure 4-5: Fleet of ships operated by Royal Arctic Line

The fleet is currently evolving towards a new strategy[27]. A new, larger ocean-going ship is being constructed which is expected to replace two of the older ships. At the same time RAL is making a strategic agreement with the Icelandic shipping company Eimskip to share vessels in the future. This vessel sharing agreement is expected to reduce overall costs plus to enable chartering of replacement vessels if existing ships are out of action for any time (as happened in 2016/2017 as described in chapter 5).

RAL is also negotiating to use the Danish port at Aarhus in addition to that of Aalborg which will allow the line to also serve other destinations in the future – such as the Faroe Islands. All these

[27] RAL Annual report 2017.

measures should enable RAL to operate more efficiently and reduce overall costs, which, whilst not of direct importance for the case, has great importance for the people of Greenland as it will contribute to growing the local economy.

RAL settlement ships deliver goods, shipped in containers, to the towns and villages of Greenland. The port logistics are managed by RAL in the 13 largest towns of Greenland with the largest operation in the new facility in Nuuk. The ships are generally following planned route activities and the deliveries are known and expected, although, the RAL master sailing plan is always tentative and reliant on ice conditions. The use of the ice-mapping services helps maintain the regularity and security of the service.

4.2.3 Tier 3: Other direct users

(a) Fisheries; Royal Greenland and Polar Seafood

Fishing is the lifeline and primary industry of the Greenlandic economy. The most commercial resources are shrimps, Greenland halibut and recently the reintroduction of cod. Greenland has the legislative competence for the fisheries sector and fishing is regulated by quotas and licence regulations on the basis of biological advice to ensure a sustainable use of the natural resources[28].

In 2017, Greenland´s fishing fleet consisted of 275 ships, 1,690 dinghy boats, 480 dog sleds and 605 snow mobiles licensed for fishing[29]. The majority of these are one-person operations or part of a small, remote community.

Royal Greenland (RG) is one of the 2 large fishing companies operating in Greenland. It is state owned whilst Polar Seafood is private. RG operates its fleet of 8 trawlers in arctic waters where knowledge of ice conditions is very important both for safety but also for accessing the richest fishing ground often found at the ice-edge. It also owns 40 fish processing plants with 35 of them in Greenland.

RG does not only operate in Greenland waters, but must go further to find fish at different times of the season as can be seen from the overall planning chart[30] in Figure 4-6. RG is operating for around 8 months of the year in Greenland waters.

[28] https://www.royalgreenland.co.uk/royal-greenland/sustainability/planet/
[29] Greenland in Figures 2018; published by statistics Greenland www.stat.gl/
[30] Royal Greenland annual report 2017.

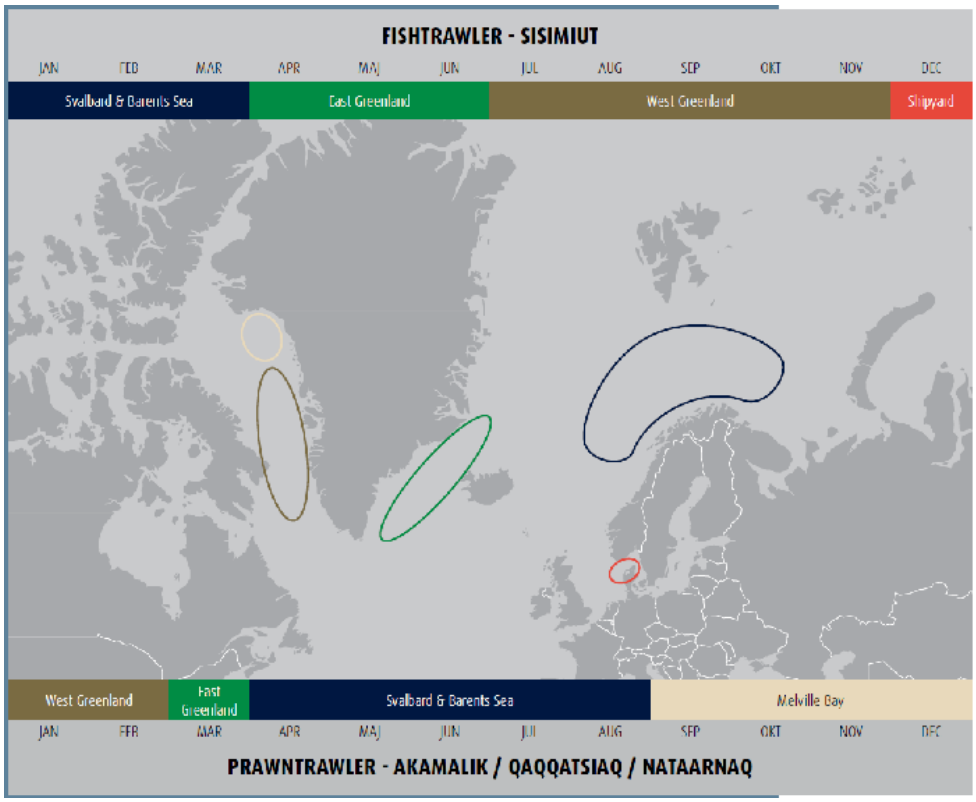

Figure 4-6: Operational picture for Royal Greenland Trawlers

RG revenues are around €800m per annum with more than 50% of these earned outside of Greenland. We have however no breakdown of where those are coming from geographically and hence the direct contribution to the Greenland economy. Nevertheless, RG employs, or is served, by over 1,900 fishermen in Greenland. Overall, the fishing industry generates revenues of €320m within the Greenlandic economy[29].

Total landings of fish and shellfish on coastal and offshore fishing, selected species

	2013	2014	2015	2016	2017
	1,000 Tonnes				
Shellfish, total	**47.7**	**44.3**	**35.6**	**44.6**	**44.0**
Snow crab	2.0	1.7	1.9	1.9	2.2
Northern prawn	45.7	42.6	33.8	42.6	41.8
Fish, total	**55.7**	**61.0**	**69.7**	**80.5**	**71.6**
Greenland cod	0.1	-	-	-	-
Wolffish	0.9	0.9	0.3	0.2	0.2
Greenland halibut	25.3	30.3	28.2	34.4	27.0
Trash fish, unspec	-	-	-	-	0.0
Capelin	0.2	0.3	0.3	0.3	0.4
Redfish	0.2	0.3	0.2	0.1	0.2
Lumpfish	14.2	8.1	7.1	5.0	7.4
Atlantic cod	14.7	21.0	33.6	40.3	36.4

Source: http://bank.stat.gl/FIE001

Table 4-1: Fish landed in Greenland.

As shown in Table **4-1**, the main two fish caught by the trawlers in West Greenlandic waters are halibut and prawns with a small amount of cod and crab. In the waters to the east of Greenland and Iceland, the catch is mainly Atlantic cod and Capelin. All catches are subject to annual quotas, agreed at national level between the Greenlandic government and the EU[31], which RG will usually attain. In addition to the trawlers, around 35% of the quota is filled by fish caught by the local fishermen. They fish in coastal waters, going out over the ice in winter, mainly fishing for halibut and some cod. On return, the haul will either be placed directly into storage or it will be processed and frozen for store.

During the winter, these stores fill up and the arrival of the first settlement ship from RAL is eagerly awaited to ship out the stored catch. If the ship is delayed, it may prevent further local fishing – as the stores are full – causing loss of revenue for the fishermen.

The other main fishing company is Polar Seafood Greenland A/S[32]; established in 1984 as the sales & marketing company for a number of independently owned Greenland prawn trawlers. Today, Polar Seafood is one of the top seafood exporters in Scandinavia and the largest privately-owned company in Greenland.

Polar Seafood operate a fleet of factory trawlers and fresh-fish vessels which include processing on-board. The group employs 900 people in Greenland and around the world. Whilst most of the fishing takes place in Greenlandic waters, as is the case for Royal Greenland, Polar Seafood operate at times of the year in waters around Iceland and Russia.

Both the fisheries companies appear twice in the value chain; at tier 3 and tier 4. They are both direct users of the services but also benefit from the service operated by RAL to carry fish from some of the local settlements back to their central processing facilities. This facet is unusual in the value-chain methodology.

(b) Ferries and Ship Chartering

Arctic Umiaq Line (subsidiary of RAL) runs a ferry between Qaqortoq in South Greenland and Sisimiut on the Arctic Circle from April until early January with the service extending to Ilulissat in the Disko Bay from late April until Christmas.

Disko Line ferries passengers between towns and settlements in the Disko Bay area, and Maniitsoq Tour Boat connect Maniitsoq with the capital Nuuk, both on a seasonal basis. And in South Greenland, Blue Ice Explorer connects a number of towns and settlements while a range of smaller charter boats are available throughout the country i.e. 30 in Nuuk for example.

Martek is one small ship charter company operating out of Nuuk. Its part-owner, Henrik Riisom Hansen, explained to us how the charter system is working and benefiting from the ice-mapping services. Henrik also downloads satellite images from NASA (MODIS optical, low-resolution images

[31] International fishing agreements:
https://ec.europa.eu/fisheries/cfp/international/agreements/greenland_en
[32] https://www.polarseafood.dk/

from the Aqua and Terra satellites) which he manages and interprets directly. The services coming from DMI enable him to plan his trips more reliably.

Martek operates 2 charter boats with a total of some 250 to 300 charters per year ranging from a few hours to a few days. The main users of the service are local people needing to move around or for pleasure, i.e. fishing. Tourism is not a heavy factor although there are signs that this may increase in the next few years.

(c) Tourism, Cruise Liners

Many companies are now offering cruises off the Greenland coast; often connecting with Reykjavik. These cruises take place in the summer months when the sea-ice is at the lowest. However, icebergs are part of the scenic offering yet a constant threat.

Every ship with more than 250 passengers on board must embark an ice pilot following the Greenlandic act in 2016. This follows the International Maritime Organisation's code for navigation in icy waters at latitudes greater than 60degrees North which includes the whole of Greenland. The Greenland Pilot Service has been established to fulfil this need.

Schedules for cruises are set some 3 years in advance; the schedule is planned, the cruise is marketed and finally the passenger list becomes complete. Approximately 45 cruise liners are active around Greenland with the cruise season lasting from June to September. Liners can carry up to 3000 passengers so the implications of an accident or even an incident (ship becoming stuck in ice) are considerable.

Safety is paramount, and the ice pilots use the ice-mapping services. The standard public service is insufficient w.r.t. frequency and timeliness, and the Greenland Pilot Service pays DMI for an improved service with much shorter latency and delivery times. Images are collected and transmitted to the pilots starting 2 days before a cruise and continue daily using whatever imagery is available.

The product is a detailed image (either optical or radar), gridded with the coastline overlaid and down to 10m resolution (or highest available) annotated with ice-observations. The volume of the image must be reduced to be transmitted to the pilots on-board the liners and hence the geographical area covered is restricted to that necessary. Clearly, the itinerary is provided to DMI before the cruise starts.

Nevertheless, the contribution of tourism to the Greenland economy is quite low but it is growing. Statistics Greenland does not have figures on the revenues generated by the tourism sector, but anecdotal evidence considered that it is low as very little of the spending finds its way into the Greenland economy.

(d) Fuel supply

Fuel transportation in Greenland is handled by Polar Oil – a wholly owned subsidiary of the Greenland Trading Company. Polar Oil operate 70 fuel bases around Greenland and the ships to transport the fuel. Fuel is the only exception to the RAL monopoly franchise for goods transportation.

Just as for RAL, the Greenland economy and way of life depends on Polaroil. It imports all gasoline, petroleum and diesel from Denmark and Gothenberg in Sweden using leased tanker services. These larger tankers will arrive in Greenland 4 or 5 times per year during the period April to November delivering to 4 storage depots in Kangerluarsoruseq, Nuuk, Kangerlussuaq, and Sisimiut. Polaroil then uses its own 2 bunker vessels to deliver the fuel on to the towns, villages and settlements to 69 tank installations throughout Greenland.

Given the nature of the cargo and the environmental threat it poses in case of accident, Polaroil main concern is one of safety. This was emphasised many times in our discussion with Niels Chemnitz. Polaroil vessels are ice-class 1A and able to break through 30cm of sea-ice. Yet the ice-mapping services are essential for Polaroil and as Niels said "*I could not imagine to sail through Greenland waters without the ice services".*

(e) Arctic Command

The (Joint) Arctic Command is a division of the Danish Defence[33] forces, established in 2012 and bringing together members of all three forces as an operational unit for Greenland and the Arctic. The Arctic Command provides surveillance and enforcement of sovereignty and the military defence of Greenland and the Faroe Islands. Other tasks are fishing vessels inspection, Search & Rescue, Maritime Pollution Prevention, hydrographic surveys, and ad-hoc support to the civilian society.

Changes in the climate, enabling increased accessibility to the Arctic, are leading to increased interest in commercial activities (oil, minerals, fishing, transport, tourism) as well as scientific activity. Hence the future of the Arctic Command will have an increased responsibility for defence and security in the region. Consequent investments are being made in new naval vessels and helicopters.

The navy vessels provide local rescue facilities and will aid civilian vessels which get into difficulties due to the ice. The Arctic Command also perform ice patrols where ice conditions are important as well as flying emergency and rescue missions throughout Greenland.

(f) Greenland Pilot Service

The Greenland Pilot Service is an organisation based in Nuuk. It was founded in 2016 after a Greenlandic act made it obligatory for all ships carrying more than 250 passengers to have an ice pilot on board. The step was considered necessary given the increasing interest in tourism in Greenland. Mostly the pilots board the liners in Iceland and disembark when they reach Canada, a journey lasting several days and necessitating to have 2 pilots on-board. For other shipping i.e. tankers or exploratory vessels, having an ice-pilot on-board is voluntary.

4.2.4 Tier 4: Business and the Local Economy

(a) Fisheries & Fish Processing

[33] http://www.fmn.dk/eng/allabout/Pages/TasksintheArcticandtheNorthernAtlantic.aspx

Unusually, the fisheries companies appear twice in the value-chain but benefiting in different ways. The fish processing plants and storage facilities for the local fishermen are served by Royal Arctic Line which ships the fish products for export. Hence, both Royal Greenland and Polar Seafood depend on the RAL service for their own businesses and hence benefit from the improvements in service which RAL derive from the use of the ice-mapping services.

RG own 39 processing facilities throughout Greenland. The newest ones are co-owned with the local fishermen; a formula which has been successful in doubling the volume of fish being caught. RG employs nearly 1400 persons in Greenland (with a further 500 fishermen depending directly on the company for their sales), a number which has grown by 50% over the last 5 years. These help RG deliver revenues of around €750m much coming from sales of higher value, processed products in markets outside of Greenland and Denmark.

Fish processing represents the key growth area in Greenland over the last 30 to 40 years. As better infrastructure has been put in place (electricity supply and communications) so the fishing industry has developed as Jens Dahl reports in his study of the Inuit community in Sassaq;

Since 1980, the harvesting of halibut has flourished and become a booming cash crop, local fish processing has created a number of salaried jobs.[34]

The inputs to the fish-processing plants are supported by the ice-services as are the exports.

(b) Mining

Mining is not a large industry in Greenland; today, it generates revenues of around €4m and employs 120 people in extracting gold ore. Yet Greenland is very rich in minerals and we heard several stories where companies had explored with a view to creating a concession, but which was abandoned once the reality of the costs were considered. There almost seems to be a business in selling exploration rights in perpetuity! Nevertheless, as the economy develops and mineral resources become more highly valued, then mining is likely to increase in the future.

(c) Supermarkets

The Greenland Trade or in the past simply "The Trade" was originally founded in the 18th century as the trading entity to serve the people of Greenland. It has gone through many significant changes most notably in the 1970's and 1990's when Air Greenland, the Royal Arctic Line and Royal Greenland were separated into new independent companies – although still state-owned – and the retail business was opened-up to competition. Now, Greenland Trade, going under the name of KNI runs many of the shops which serve the Community as well as Polar Oil (see above).

KNI operate the Pilersuisoq chain mainly in the smaller, more remote towns, supported by a government subsidy. Several attempts have been made through the years to create a competition which largely failed until, in 1993, a second supermarket chain, Pisiffik, was set up by the Greenland government to operate in the larger towns without subsidy and to an extent to compete alongside Pilersuisoq. In 2001, this was sold to another Danish company Dragofa.

[34] Saqqaq: An Inuit Hunting Community in a Modern World. Jens Dahl, University of Toronto Press, 2000.

(d) Construction

The construction industry is worth around €300m per annum in Greenland (see Table 2-1). A lot of this is in Nuuk which is growing rapidly. Another part is in the construction of hydro-electric works as the demand for electricity increases. All construction materials are imported to Greenland through RAL. The benefits to this sector are small as construction work stops in the winter whilst material is imported ahead of the schedule.

4.2.5 Tier 5: Citizens and Society

Ice is a factor which influences the whole of the Greenland society. Essentially nothing is left untouched to the extent that even the Danish government subvention is influenced by the geo-politics of the ice-bound island. Growth in the Greenland economy supports the citizens, increase their annual income and renders their lives easier. Fishing has been the main motor of this growth in recent times and referring again to Jens Dahl,

Fishing and fish processing are the factors that more than anything else have changed the West Greenlandic communities. Since the world war II, thousands of people have left the settlements of West Greenland to base their lives on the booming fishing industry in towns like Illusiat, Sissimut, Nuuk and others.[34]

Hunting has been a way of life in Greenland for generations. Even today, hunting provides an important supplement to household economy. Hunting is regulated by means of seasons and permissions. Hunting is controlled with annual licenses and quotas strongly enforced. Table 4-2 shows the number of mammals caught each year by Greenlandic hunters.

	2012	2013	2014	2015	2016
Seals	124,319	149,678	131,893	123,927	86,343
Whales	3,894	4,119	4,133	3,094	3,410
Land Mammals	17,855	17,658	19,460	18,119	16,928

Table 4-2: Number of mammals and birds caught

The other major factor has been the migration of people into the towns where economies of scale make growth easier and life more comfortable. In Nuuk, we saw a whole landscape already laid out with roads and infrastructure ready to be built upon as people arrive. This in itself drives growth and the economy benefits.

One of the key goals is for the island to become fully independent without reliance on the annual subvention from the Danish government. Growth in the economy is a necessary precursor to achieving this goal.

4.3 Other Transversal Actors

The key actor is the Greenlandic, home-rule government formed after Home Rule was determined in 1979 with further devolutions of power in 1985 and in 2009. The influence of the government is seen from the fact that 40% of jobs are in the public sector: administration, health, teaching, roads etc. In addition, the largest businesses are also publicly owned and hence the role of the home-rule government in the economy is particularly strong.

Given the importance of the public role, the impact of the ice-mapping services is also strong with a strong influence over economic growth and evolution. This is a strategic dimension which we'll return to in chapter 5 when dealing with the benefits.

At the request of the Home Rule government, a group was established called the Nautical Committee in May 1998. The Nautical Committee is a member of the Ministry of Housing, Construction and Infrastructure. The purpose of the Nautical Committee is to establish a forum of maritime experts who can provide feedback on legislative action by the Danish Maritime Authority, and discuss other issues within the maritime area - including external inquiries. Nautical Committee members consist of representatives of the maritime industry in Greenland and the home-rule Government, designated by the Ministry of Housing, Construction and Infrastructure.

5 What are the Benefits?

5.1 Overview

The benefits in this case are complex to analyse as ice and the ice-mapping services go to the heart of the Greenlandic people. Ice dominates their lives and hence a service which makes their lives easier and safer has a great importance. At the same time, that there are only some 55,000 people living on the island means that although the value to each inhabitant is great, the total value is still limited.

The benefits to Greenland (and indeed to Denmark) of the ice-mapping services is quite fundamental and touch every part of life on the Island. Coupled with the geo-political importance of Greenland, increasing as a result of the changing climate and opening up of the Arctic Region, this means that the ice-mapping services are quite strategic in nature. This makes calculating the benefits very hard since rarely is value placed directly on a strategic asset.

Our approach will be to focus first on the operational aspects where, with the aid of assumptions, we can arrive at a direct benefit and then secondly discuss the strategic benefits and attempt to place some value upon them.

5.2 Operational Benefits

5.2.1 Tier 1: Service Provider

The ice-services provided by DMI have developed with the availability of Copernicus Sentinel data and especially Sentinel-1. The ice-services provided by DMI are partly financed by the Danish government and further supported by RAL and the Greenland government.

Up until the end of 2017, the Ice Patrol in Narsarsuaq was manned by 4 persons in shifts with a helicopter based there used for ice reconnaissance flights over the region. The availability of Copernicus Sentinel data and replacing the helicopter reconnaissance with satellite-based services led to improving the regularity and quality of the ice information.

The transition to 100%. satellite-based services led also to an efficiency gain for DMI, which partly has been reinvested into a commercial contract with the Norwegian Kongsberg Satellite Services (K-SAT) to provide at least a weekly coverage of Southern Greenland using TerraSAR-X (TSX) ScanSAR images to complement Copernicus data. These are used for the inshore mapping in South Greenland that was previously covered by the helicopter. The TSX works as a supplement to the Sentinel-1 acquisition cycle over South Greenland and TSX images are acquired in the gaps between Sentinel-1 images, to provide better update frequency.

Further radar images are taken from the Italian Cosmo-Skymed satellites and the Canadian Radarsat-2 satellite and are provided by the European Commission as contributing missions to the Copernicus programme. These are available to the DMI ice service at no cost as a result of DMI being a service provider in CMEMS.

All of the users we talked to emphasized their wish for more regular updates to the ice charts. The movements of the ice, often under extreme weather conditions, means that routes and passages can open and close rapidly. All users reported themselves happy with the decision taken by DMI to switch to the satellite-based service, even if they were concerned at the time when the closure of the Ice Patrol was first announced.

Economies made by DMI are offset by the purchase of commercial satellite imagery to provide the required regularity of ice maps. The improved services offered by DMI should be reflected in more benefits further down the value chain. However, these may not yet show up in the deeper analysis today. Overall, the benefits to DMI are considered neutral (ie zero) in terms of Euro although there is a reputational benefit coming from an improved service.

5.2.2 Tier 2: Primary User

The primary user in this case is the Royal Arctic Line due to their position as sea-transporter of all goods entering or leaving Greenland. Here we consider 2 main categories of economic benefit; operational cost savings due to improved navigation, exceptional costs savings through reduced accidents or incidents (trapped in the ice).

(a) Operational cost savings arise as the ships are able to reduce delays and select the better routes to avoid the ice.

RAL, and other shipping operators, are using the ice charts and the quick-look images to avoid the ice or to identify where the ice is difficult to sail through. This is primarily in the Southern areas of the island where the ice-monitoring centre was operating in the past but also up the west coast. As the ice develops in the winter season or is melting in the spring, the conditions are very important to assess as they change quickly. According to DMI, once the images are over 6 hours old, they are almost of no value due to ice drift. Clearly, this is relative to the situation, but we can see that fresh images are important for the users.

Elsewhere in Greenland, further north, the ports are more-heavily ice-bound. Here the ice-charts and satellite image quick-looks are allowing those planning the ships operations to judge whether a port can be accessed. This becomes particularly critical at the start and end of the ice season. We were told that RAL endeavours to ensure that each settlement gets a last delivery before Christmas i.e. in December whilst as the ice melts, gaining access is most important to replenish supplies after the winter and from a business point of view to empty the fish stores – we shall return to this later.

We have made the assumption that the services are able to save each ship 10 days of operating time each year. RAL are currently operating 6 settlement ships, 3 larger ships around the Greenlandic shores (between terminals) and 2 “ocean-supply ships. We are working with the assumption that the ice-services are of most benefit to the ships operating close in-shore, although there is certainly some benefit for the other ships as well. Our assumptions and calculation of the economic benefit are set out in Table **5-1** below.

(b) Accidents happen with ice collisions as well as incidents where the ships may be trapped in the ice.

We heard specific examples of both during the interviews in Greenland. RAL had an incident last year where a settlement ship hit an iceberg causing damage to the ship and propeller. The cost was significant. The trip which should have taken 12 hours took a total of 3 days. The ship was out of action for 6 weeks as it was towed to Nuuk for repairs. The rescue was carried out by the Arctic Command so there was not a direct rescue cost but RAL had to charter another ship for the duration at a cost of €10k per day. The total cost to RAL was upwards of €120k.

This type of incident is rare, and the ice-services help to avoid them happily making them even rarer, but there is no information or statistics allowing us to compare the likely frequency of such accidents with and without the ice-mapping services. If we assume that these can help avoid an accident once every 4 or 5 years, the average saving (based on the cost to RAL last year) will be around €25k to €30k per annum.

Similarly, there are incidents when ships get trapped in the ice, necessitating rescue – normally by the Arctic Command. The cost is the loss of operation of the ships for the days which are lost. There is also a disruption cost due to rescheduling of sailings for other supply ships. From Arctic Command we heard that there are 3 to 5 such incidents each year. It seems not unreasonable to say this could be double if the ice-mapping services were not available, but this benefit is not included below, but will be assigned under the Arctic Command.

Ship Type	Number	Days Saved per ship per annum	Cost per day	Fuel cost per day	Benefit
Settlement	6	7	€8.4k	€5k	€563k
Supply	3	3	€8.4k	€8k	€148k
Ocean	2	2	€8.2k	€8k	€65k
Reduction in costs associated with accidents and incidents					€30k
Total benefits (rounded)					€800k

Table 5-1: Benefits to RAL ships from using the Ice-mapping services

5.2.3 Tier 3: Other Direct Users

(a) Fisheries

The two main fishing companies, RG and Polar Seafood operate 8 trawlers between them. Not all the time is spent in Greenland waters although the ice-mapping services also operate off Svalbard and the Faroe Islands where some of the fishing takes place. The trawlers can operate more efficiently as a result of knowing where the ice is located. This enables them to save fuel and to increase the value of their catch. Since there are quotas applied to their catch, the quota can be reached more quickly through the use of the services. We have not specific numbers from RG or PS and so use the same cost figures as for RAL.

The trawlers operate around the edge of the ice where the halibut fish are most numerous and having this precise information from the ice-mapping services enables the efficiency gains by the trawlers.

In-shore, where the shrimps are caught, the trawlers are assisted to avoid the ice much as is the case with the cargo ships of RAL and Polaroil, the cruise liners and the naval vessels of the Arctic Command. Being able to operate further north, which is the case aided by the ice-mapping services, allows larger and more valuable shrimps to be caught.

Hence the benefits come from reduced operational costs and improved safety for the ships and more valuable catches for the companies. The total catch in Greenland is valued at €300m. If we assume that the ice service contributes 0.1% to this, it generates a benefit of €300k per annum. Added to the days saved through avoiding ice as shown in Table **5-2**, the total benefit to the fishing sector is estimated at €840k i.e. around €420k to each of the two major fisheries companies.

Ship type	Number	Days Saved per ship per annum	Cost per day	Fuel cost per day	Benefit
Trawler	10	3	€10k	€8k	€540k
		Total catch value	**Contribution from ice-services**		
Efficiency savings/greater catch		€300m	0.1%		€300k
				Total Benefits	€840k

Table 5-2: Benefits for the Fishing Companies from the use of the Ice-Services

This is not the whole story for the fishing industry. Further small trawlers are operated by fishermen along the coast. We shall consider the benefits under the section dealing with citizens and society.

(b) Ferries and Ship charters

After the M/S Hans Hedtoft struck an iceberg and sank off the southern coast of Greenland, the airbase in Narsarsuaq was reopened as a rescue centre. It also led to the ice monitoring centre for aircraft to fly over and survey the ice. It left a strong mark on Greenlandic life and a strong motivation to avoid accidents involving passenger ferries.

Additionally, ships do sometimes get caught in the ice so taking them out of service for a few days. From the Arctic Command we heard that the naval ships will rescue trapped civilian ships between 3 and 5 times per year. The number is much higher for smaller craft. We heard about a passenger ferry operated by the Arctic Umiaq Line which became trapped in the ice with a full passenger list of college students returning to Copenhagen for the next year of studies. The ferry was trapped for nearly 1 week. Amusingly, for the young passengers it became party-time but for the ferry company it was a major headache to free the ferry and to re-establish the ferry schedule.

This also illustrates something we heard many times in Greenland. Since the ice controls people's lives, Greenlandic people are extremely patient. Delays to ships or aircraft due to the weather, even for several days or weeks, are accepted as a part of daily life. The longest delay narrated to us was a flight which took off 49 days late!

Ship charter is a significant business in Greenland with around 30 vessels in Nuuk. Lacking any figure for the rest of the island, we shall assume the same number of boats for a total of 60 in Greenland. This excludes private vessels which may be hired from time to time.

Charter rates work out at €1000 per day or even higher for a vessel with capacity for 30 people. Mostly the charters are for fishing trips but with some tourism and simple transportation. Martek with whom we talked has recently sold its larger vessel as being uneconomic to operate so as to focus on smaller vessels with a capacity of up to 12 persons. Martek operate 250 to 300 trips per year from a few hours to a few days in duration using 2 boats.

Another use is the transportation of crews to remote hydro-electric plants or construction sites which may include new power generation sites. Hydro-power is becoming an important source of energy for Greenland where demand is increasing as the economy grows.

Martek use the ice-mapping services to assure their charters. In other words, before signing a charter and setting out, the ice charts and images are used to be confident that the boat will not become trapped in a port or any other destination. This enables Martek to complete more days hire in the year than would otherwise be the case. Martek use the DMI services but the part-owner, Henrik Rilsom Hansen, has also discovered a service from NASA using MODIS imagery from the Aqua and Terra satellites. Ice images are not needed all the time; only when the temperature is colder than -5 degrees and when it is necessary be aware of ice conditions is closing or opening.

To calculate a value, we use the same method based on the number of ship sailing days which are saved.

Ship Type	Number	Days Saved per ship per annum	Cost per day	Fuel per day	Benefit
Ferries	5	5	€6k	€4k	€250k
Charters	60	3	€1k	€0.5k	€290k
				Total	€540k

Table 5-3: Benefits accruing to passenger ferries and charter boats.

The other benefit arises from the reduced risk of accidents which for passenger shipping especially is of primary concern. There are no benchmarks to work from for this factor and so, whilst it is significant, the best way to address this would be through insurance rates for the boats in case of accident but we did not manage to access figures for this.

(c) Tourism and cruise liners

Tourism is increasing in Greenland mostly through cruises to the east and north-east of the Island as well as to Disko bay on the western coast and nearby glaciers. The key factor is safety with the need to ensure this at all costs.

For the cruise operators, they have a reputational risk, with maybe the risk to pay compensation if a cruise does not fulfil the conditions offered. Hence ice statistics are used to identify the areas which are safe. Therefore, the benefits identified for other shipping through sailing days being saved is not really present. If the risk is too high, then the destination will not be included in the cruise itinerary.

Where the ice-mapping services play a role is to inform the pilots on daily conditions, to plan routes and to open-up new destinations which would otherwise not be accessible without the information coming from the ice charts.

Consequently, of the around 40 cruises operating in Greenlandic waters each year, one or two at each extreme of the season may be considered to be made possible through the application of the ice-mapping services ie the risk is reduced to a minimal level through the use of the ice-mapping service. The numbers of cruise passengers for different seasons and over the last 5 years, is shown in Table 5-4.

	2013	2014	2015	2016	2017
Winter					
Spring	206	293	163	562	185
Summer	9,564	13,594	15,791	17,089	17,506
Autumn	11,726	6,327	9,095	6,593	9,734
Total	21,496	20,214	25,049	24,244	27,425

Table 5-4: Numbers of cruise ship passengers

If we assume that 2 additional cruises are made possible each year by the ice service, with an average of 2000 passengers on board and if each passenger is paying €2,000 for their ticket, the 2 extra cruises are worth €8m revenue for the tour companies. But only a very small fraction of this is adding value to the Greenlandic economy. We shall assume that 5% of the price paid by the passengers ends up benefiting the Greenland economy through various means; payments to the ice pilots, passenger spending on souvenirs, visits etc.

Ship Type	Number of passengers	Extra cruises	Price per passenger	Total revenue	% in Greenland economy	Benefit to Greenland
Cruise liner	Min: 2000 Max: 3000	2	€2000	Min: €8m Max: €12m	5%	Min: €400k Max: €600k

Table 5-5: Benefits of the ice-mapping services coming from cruise industry

Benefits to the cruise ships at other times of the year are harder to calculate. They are largely through the avoidance of changes to planned cruise programmes and through improved safety. The benefit is realised through the use of the ice-pilots.

(d) Fuel Supply

The value of the ice-mapping services to Polaroil is considerable both for strategic planning of the deliveries throughout the year and for operational decisions and planning on a weekly or even daily basis. When DMI closed the ice centre in November 2017, there was a lot of concern for the impact on Polaroil operations. Yet, it is now considered that the new service is better and provides better support for their planning mainly due to the increased frequency of information on the ice conditions.

We understand that the value of the services to Polaroil varies from year to year. For example, 2018 was colder than previous years (we heard this during a number of interviews) posing a significant problem for Polaroil. If no ice service had existed, it would have been much more difficult to plan and to re-plan the deliveries so as to ensure that all settlements were served ahead of the winter.

Polaroil operate 2 tankers delivering fuel around the Greenland coast; 1 is operating all year round, the other for about 4 months of the year. Together they are making between 30 and 50 trips per year serving the communities.

As in the other cases of shipping using the ice-mapping services, the benefits are a reduction in voyage time and reduced risk of accidents and incidents. The value of the ice-mapping services is mainly during the early winter and spring seasons when the ice is changing most significantly. Thanks to better knowledge of ice conditions; ships can reach the settlements as soon as it is possible: "no additional waiting time as safety buffer".

We make the assumption that 0.5 days per voyage are being saved by using the ice-mapping services.

Ship Type	Number of trips p.a.	Days saved per trip on average	Ship cost per day	Benefit
Tankers	Min: 30 Max: 50	0.5	€10k	Min: €150k Max: €250k

Table 5-6: Benefits to Polaroil from the use of the Ice-Mapping Services

(e) Arctic Command

The Arctic Command are using the ice-mapping services in two ways:

A Danish defence special unit, the SIRIUS dog-sledge patrol that operate in the vast National park of Northeast Greenland, receive custom made ice charts of their routes on the land-fast ice. The collaboration with the DMI Ice Service was initiated after a tragic loss of two SIRIUS dog-sledge

drivers that went through thin ice in 1999. Here the value of the information is very hard to assess but we are told that their job would not be possible or rather would not be safe without the ice information. We shall consider this value to be part of the overall strategic benefit to Greenland (and Denmark).

For their naval vessels which are used for patrols around the coast and for rescue operations when ships become stuck in the ice. Interestingly, as one of their roles is to watch for oil spills, the Arctic Patrol are using the Copernicus Services from the European Maritime Safety Agency (EMSA) to survey the sea and the ice – since they prefer to use the common platform provided at European level. The DMI services have been used much more for statistical analysis of where the ice is present and when and how it is changing over the years.

Nevertheless, it is still using data from Sentinel 1 and hence we shall include the benefits to the Arctic Command notwithstanding the delivery channel.

According to Rasmus Kimer with whom we talked, the number of sailing days for the naval vessels is a KPI for the Arctic Command. On average, 5 ships will be in use throughout the year. Getting a naval ship stuck in the ice would be a major disaster for them and so they are doing everything to avoid that. Should it happen, then they would lose an estimated 60 to 100 sailing days. This could be a good measure of the value of the ice-mapping services to the Arctic Command.

Ship Type	Number	Days Saved per ship per annum	Cost per day	Benefit
Naval vessel	5	Min: 12 Max: 20	€10k	Min: €600k Max: €1m

Table 5-7: Benefits accruing to Naval vessels of the Arctic Command.

(f) Greenland Pilot Service (Ice Pilots)

The ice-pilots plan their services in May when the cruise liner schedules are finally fixed and published. Around 10 highly experienced and qualified pilots are working for the Ice Pilots. The DMI services are considered *"extremely important"* according to Thomas Bøggild with whom we spoke. The planned schedules for the cruises are sent to DMI in order that imagery can be prepared for the areas visited to be available as the cruise liner arrives.

The pilot starts to receive images 2 or 3 days before the cruise departs so as to develop a picture of the ice conditions where they will be sailing. The images are quick looks as described in section 3 and are delivered by e-mail. Timeliness is highly important.

The cost of the Ice Pilots service is around €2k per pilot per day. For a cruise liner operating in Greenlandic waters for 5 days with 2 pilots on-board as required by the Greenlandic legislation, this is a total cost of €20k for the pilot services. We shall make the assumption that the benefit of the ice-mapping services to the pilots is around 25% of this ie €5k per cruise, which for 45 cruises per year is a total benefit of €225k.

5.2.4 Tier 4: Business and Local Economy

In tier 4, we consider the secondary economic benefits from the use of the ice-mapping services, i.e. the businesses which are better served and can operate more effectively. We consider this only for business located in Greenland although there will be some benefits for businesses in Denmark. There are 3 beneficiaries considered in this tier.

(a) Fisheries & Fish Processing

This is an unusual situation (for the cases which we have so far studied) where the same beneficiary appears twice at different parts of the value-chain. Here the fisheries are not only benefiting directly from the ice-services, but they also benefit from the service provided by another user; in this case the primary user, RAL.

RAL transports the fish which have been caught by local fishermen and processed in local factories and which are stored until the RAL ship arrives to embark the fish products. In the summer, the RAL ship arrives regularly, but throughout the winter the settlements are ice-bound and can only transport goods by sleds over the land-fast ice. The RAL ship is important to empty the storage chambers before the onset of winter and to do the same as early as possible after the ice is melting to make space for the new catch.

The value of the fisheries industry to Greenland is €300m and Royal Greenland told us that 35% of their catch comes from the local fishermen. Let us assume that the RAL shipment saves about 1 week of the catch i.e. €2m. How much of this is enabled by the ice-services? It is quite significant for sure, so we take a range of 10% to 20% of the total value as being the benefit generated by the ice-services i.e. €200k to 400k.

(b) Mining Companies

Mining is a relatively small economic activity; worth around €25m in each of the last 2 years. Although Greenland is rich in minerals, the cost of extraction is very high due to the hostile climate and, consequently, few projects reach maturity to start operations. Instead there are many prospecting and evaluation projects. Each time the prospective concessionaire is paying a fee to the Greenland government and it is almost a business in its own right to trade prospects!

A major prospect has recently been investigated by a Chinese team looking for rare earth minerals. An evaluation was made leading to a proposal to invest in the airport at Nuuk to enable the mining operations. But this proposal was withdrawn when the Greenlandic and Danish governments decided to make the investment themselves.

Each prospect requires evaluation teams to be dispatched into the wilderness which require support ships and which in turn benefit from the ice-mapping services. What value to assign? We shall place a modest €100k per annum on this benefit but with little concrete information with which to back it up.

(c) Supermarkets

As we saw in the Baltic case[23], supplying the supermarkets and keeping the shelves full is a major comfort to the local citizens. In this case, the KNI (ex Greenland Trading Company), which is the

main operator of large shops in Greenland, also owns the oil distribution company and the supply of petrol. All this illustrates the circular nature of the Greenland economy, the influence which ice has on the economy and the consequent importance of the ice-mapping services.

From **Table** 2-1, we see that the trade is worth some €1.3b. All the products of this trade are carried by the RAL (apart from a small amount of air-freight) where the delivery is made more reliable by the use of the ice-mapping services. How much value to place on this component?

The benefit to KNI comes from being able to organize storage and store logistics more effectively as well as the onward distribution between their stores. If we assume that the cost of these operations to KNI is around 2% of the gross revenue i.e. €26m and that the improvement in logistics enables a 1% to 2% saving on these costs, the benefit to KNI of the ice-mapping services is then estimated at €260k to €520k. In other words, KNI would see costs increase by this amount if the ice-mapping services were not made available to the RAL.

(d) Construction

The construction sector is worth around €300m per annum and all the materials are transported by RAL. Whilst there must be a benefit to the sector derived from more predictable delivery times, the planning of the construction work will accommodate these variations. We shall not put a figure on the value as we consider it will be very low.

5.2.5 Tier 5: Citizens and Society

Clearly the citizens are benefiting from the ice-mapping services in many, many ways. Indeed, any growth in the economy is only possible through the use of the services which keep the goods transported both into the country and out of it.

In the Baltic case, we made a thought experiment around the willingness to pay i.e. the amount a citizen would be prepared to pay each year to be assured of having food in the supermarket, drugs in the pharmacy and petrol in the gas stations. This is also true in Greenland although the strong integration of government (public sector) into every part of Greenlandic life means that the citizens would surely see this as being a responsibility of their government.

Part of the society are the individual hunters and fishermen who also benefit from the transportation made by RAL. They also benefit directly from the ice-services – as we saw in the small anecdote narrated at the beginning to introduce the case.

Hence, to use a similar willingness-to-pay approach as we did in the Baltic is reasonable. Even so, we are somewhat reluctant as it is not based on a survey or on facts. In the Baltic case, we used a figure of €1 per day as the amount the citizens would be willing to pay. If we were to use the same in this case, it would yield a total value of €20m. But this is the total value not the contribution coming from the use of Sentinel imagery. In the Baltic we used a range of 0.1% to 0.5% as the contribution from the imagery, which would be €200k to €1m for the Greenland citizens and society.

5.2.6 Other Beneficiaries

The two governments of Greenland and Denmark also benefit from the ice-mapping services; both in an operational sense to keep the country running well and strategically. For Denmark, the value is to support economic activity on the island with two consequences. Firstly, to underpin the geopolitical advantage which Greenland brings to Denmark as a stronger, global player. Secondly, to provide access to the polar regions which can be seen as geopolitical or as simply a bet on the presence of natural resources. Thirdly, to enable growth in the Greenlandic economy and hence to reduce the subvention necessary – but which has no direct value other than a historic obligation and to enable the geopolitical benefits.

Following World War II, the United States developed a geopolitical interest in Greenland, and in 1946 they offered to buy the island from Denmark for $100m[35]. Using figures from the US bureau of labour statistics[36], the value of one dollar in 1945 is equivalent to $13.6 today. Hence the $100m in 1945 would be equivalent to $1.36b (€1.1b) today. Denmark turned this offer down which, according to Gwern Branwen[37], was a mistake.

The value to the US was higher at that time than it would be today and through agreements with Denmark (and NATO) the US is able to operate the Thule airbase on Greenland and has achieved its objectives at much lower cost. Why did Denmark turn the offer down? We should like to conclude that there is a strategic value to Denmark in owning the island, but this case is hard to make.

A further indication could be obtained by looking at the Chinese offer to invest in infrastructure in order to open-up mining operations. The Chinese interest in rare earths is well known and today, China supplies around 90% of the world market; hence their interest to gain access to a new supply in Greenland. Notwithstanding that rare earth elements s are not so rare, the Chinese offer to invest in a new airport in Nuuk demonstrates a strategic perspective which is further re-enforced when the offer is not accepted. The cost of new airports vary enormously and of course a Chinese investment is not the same as buying Greenland as the US tried to do.

Greenland gives Denmark access to the islands' minerals and to the Arctic. Indeed, according to an analysis by Torben Andersen[38]:

> *Greenland is a vast country with a small and geographically dispersed population. These conditioning factors pose a particular challenge for a natural-resource based economy. Greenland is thus in many ways unique and has yet to find a way to ensure a self-sustaining economy.*

The €450m annual subvention from Denmark to Greenland is a necessary input to the economy until or unless Greenland can become self-sufficient. For this to happen, the mining sector would

[35] Wikipedia: Denmark-United States relations; https://en.wikipedia.org/wiki/Denmark%E2%80%93United_States_relations
[36] http://www.in2013dollars.com/1945-dollars-in-2017?amount=1
[37] https://www.gwern.net/Greenland Why didn't Denmark sell Greenland?
[38] The Greenland Economy: Structure and Prospects. Torben M Andersen, Working Paper 2015-14, Department of Economics, Aarhus University. June 2015.

need to grow substantially which is not the case today. Indeed, if the natural resources industry (including oil and gas) were to develop sufficiently, the agreement between Denmark and Greenland foresees an end to the subvention.

We can use this as a starting point for calculating the strategic benefit. Discounting the €450m at 3% per annum out to 2050, gives a valuation for Greenland of €9b; way in excess of the valuation placed on it by the US. Of course, the subvention underpins the monopoly in shipping enjoyed by RAL and which in turn means that 90% of the imports and exports flow through Denmark. In other words, there is a direct trading value resulting from the subvention.

A further "benefit" derives from the subvention through it being accounted as a part of the Danish contribution to NATO. This is part of the defence force to oversee and protect the Arctic as well as to enable a US airbase on the island. Plus of course this brings obligations such as the need to maintain the Arctic command.

In his analysis, Gwern Branwen looks at both the benefits coming from investing the €100m as well as the savings in subventions paid over the time. He also analyses the reasons why Denmark may have decided to keep Greenland from an economic view. He concludes with a statement made by Hans Hedtoft, Danish prime minister at the time:

> *"Why not sell Greenland? Because it would not be in accordance with our honour and conscience to sell Greenland. The Greenlanders are, and feel they are, our countrymen and we feel tightly bound to them. It cannot be our generation's task to make the Danish state smaller, and it is not in accordance with the policy of the Danish government or the wishes of the Danish people."*

The strategic value of Greenland extends much beyond Denmark. Eight states have territories in the Arctic: Canada, the Kingdom of Denmark, Finland, Iceland, Norway, Russia, Sweden and the United States. Three EU Member States are therefore also Arctic states, while Iceland and Norway are members of the European Economic Area.

> *"A safe, stable, sustainable and prosperous Arctic is important not just for the region itself, but for the European Union (EU) and for the world. The EU has a strategic interest in playing a key role in the Arctic region."*[39]

The EU cooperate with all Arctic partners, including Canada, Russia and the United States. The EU co-operates with Greenland under the EU-Greenland Partnership which supports Greenland in addressing its major challenges, in particular the sustainable diversification of its economy and strengthening its administrative capacity. The EU provides budget support to Greenland with the aim of strengthening the education sector as a driver for sustainable development. The EU will further engage in policy dialogue at the appropriate political and technical levels on issues of

[39] JOINT COMMUNICATION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL An integrated European Union policy for the Arctic: JOIN(2016) 21. 27th April 2016.

common concern, such as global issues (energy, climate change and the environment, and natural resources) and Arctic issues.

Thus, the value of Greenland is clearly seen as being strategic not just for Denmark but for several actors in the Arctic region. In this case, the value of Greenland could easily be considered around the €1.1b representing today's value of the €100m offered by the US in 1946 and maybe is even closer to the €9b derived from the discounted subvention. The DMI ice-mapping services are a key part in enabling the economic development of Greenland; the strategic value of the island is underpinned by a developing economy and population which both depend on the ice-services. Further economic development will only bring heavier demands.

All this is to back up the argument that placing an economic value on the strategic benefit is highly uncertain – whilst the context suggests strongly that there is a value to include. So, what is the value of the benefit coming from the ice-services? As a means to provide a value in a rational way, we shall assume that the strategic benefit is the same as the operational benefit i.e. the total will be doubled. There is no real logic behind this other than to find a rational way to add a figure for the strategic value. Our feeling is that this greatly underplays the value, but we cannot find quantitative arguments to justify this.

5.3 Environmental Benefits

The ice-services themselves generate very little benefit directly in terms of environmental factors. There may be a very small saving in fuel but even this is not a given as sometimes the ships may take longer routes to avoid the ice; so consuming more fuel. Indeed, the increased tourism leads directly to increased fuel use and other polluting affects.

Reduced risk of accidents and potential oil spills can be considered as a benefit to the environment which may become more significant in the future as shipping increases and especially if oil exploration and extraction increase. Cleaning oil spilled in cold waters is much harder than in warmer regions and so avoidance becomes the main policy.

In the longer term, climate change will alter shipping conditions in Greenland as was discussed in chapter 2.5. The impact will be to increase the need for the ice-services. Increased ship passages whether for cargo (RAL), fisheries (RG), mineral exploration (charter) or tourism (cruise liners) will all require more punctual and accurate ice charts and images. The value of these services is not likely to decrease.

Information on the ice coming from the satellite images is used heavily in research into the environment and climate change. Indeed, many of the earth observing missions are launched on the basis of polar and climate research. Here the value is very high but it is not the central use of the images discussed in the case.

5.4 Summary of Benefits

Table 5-8 gathers the benefits together to give the total economic value. These are organised by the Tiers and the ranges given where appropriate.

The total value of the benefits is shown for the contribution made by the ice-mapping services provided by DMI. It lies between €8.6m and €12.5m per annum. Half of this is due to the direct operational benefit which has been calculated and half due to value ascribed for the strategic benefit to Denmark and the Greenlandic people.

		Min	Max
Tier 1: DMI		€0k	
Tier 2: Royal Arctic Line		€800k	
Tier 3: Other Direct Users			
	Fisheries	€840k	
	Ferries and Charter Boats	€540k	
	Cruise Liners	€400k	€600k
	Polaroil (fuel supply)	€150k	€250k
	Arctic Command	€600k	€1000k
	Greenland Pilot Service	€220k	
Total Tier 3		€2750k	€3650k
Tier 4: Business & Local Economy			
	Fisheries	€200k	€400k
	Mining	€100k	
	Supermarkets	€260k	€520k
	Construction Sector	0	
Total Tier 4		€560k	€1.020k
Tier 5: Citizens and Society		€200k	€1m
Other Beneficiaries (strategic value)		€4,310k	€6,270k
Total Economic Benefits		€8,620k	€12,540k

Table 5-8: Summary and total of the Economic Benefits

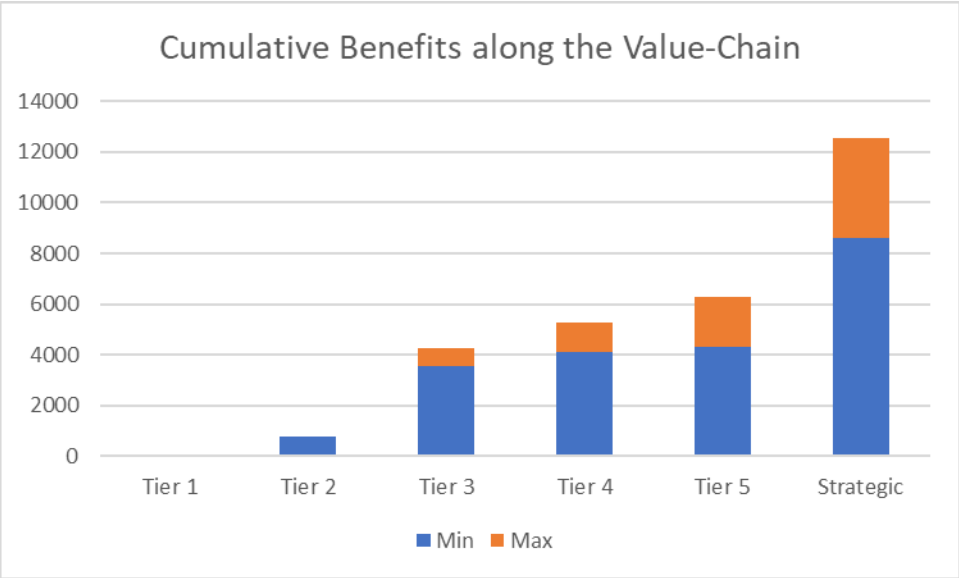

Figure 5-1: Cumulative Benefits along the Value-chain

Figure 5-1 shows the benefits along the value-chain accumulated at each tier. We decided to keep the strategic benefit separate to ease identification in the future although it should arguably be considered as part of the tier 5 (citizens and society). It shows a progression indicating that the impact of the ice-mapping service passes along the value-chain to the businesses and to the citizens.

6 Conclusions

6.1 Summary of Findings

The ice-mapping services provided by the DMI play an extremely important role in the daily life of Greenlandic people. Ice is a daily factor in the life and having a picture of where the ice lies, is invaluable to the local population and the development of the Greenland economy.

The benefits are operational and strategic. The operational benefits, which do cascade down the value-chain, arise largely through the possibility to avoid delays and even accidents in the ice-bound waters. The strategic benefit is very clear but impossible to calculate; hence we have made a very basic assumption to derive a figure.

The total benefit we have estimated is between €8.6m and €12.5m which seems a modest number given this extreme importance. This has to be considered against the small population of Greenland (56,000), meaning the benefit is up to €200 per person per annum. This is made up of €100m per head for the operational benefits which compares with the €90 per head we have seen in the Baltic[41]. In other words, the operational benefits are really quite similar whilst the strategic benefits add further value.

This does not seem unreasonable given the differing contexts.

The objective of the ice-mapping services for Greenland is similar to the Baltic case; to guide ships through icy waters. Yet the precise objective differs i.e. to avoid ice rather than to find the easiest path through it as well as the means of delivery and implementation of the service. In the Baltic, ice-breakers are used to guide ships which are not well-adapted to sailing in ice conditions. Whilst in Greenland both the ships and the captains are adapted and ice-breakers are not used.

6.2 The Impact of Sentinel Data

The impact of Sentinel data on the ice-mapping service has been quite deep. Since November 2017, when the ice centre in Narsarsuaq was closed, the service has become dependent on the use of SAR satellite imagery. The start of operational services from the EU Sentinel satellites was fundamental to this decision. Indeed, the operational nature of Copernicus has been fundamental in enabling organisations (users of EO services) to change their processes.

Before Copernicus, and it must be said the launch of a number of private constellations of satellites, a limited number of satellites delivered images and it was too risky for an organisation to switch the process to depend upon them. Now, the many different and complementary sources (DMI are taking Sentinel, TerraSAR-X, Cosmo-Skymed, and Radarsat data and will soon be able to also acquire SAR images from IceEye and from NovaSAR) means that the risk of complete failure is very small.

Copernicus, with its free and open data policy, has been able to establish a public, backbone with other, commercial data complementing it. It has been quite a gamechanger for DMI and for Greenland. How much of the benefit is due to the Sentinel's?

For the Baltic case, we faced the problem to evaluate the value of the ice-breaking services (i.e. the value of the ice-breakers themselves to the Finnish economy). We had been surprised to find that this was not known (or maybe was not available to us) but that there was (and still is) an exercise to model and calculate this value. We would then need to analyse how much of this value (what percentage) could be attributed to the use of the Sentinel data.

Since we started from the basics, we used a statistical approach based on the deviation from expected arrival time for the ships to help analyse the value, coupled with assumptions on the statistical distribution. We then assigned a fraction of this total benefit as being attributable to the satellite imagery.

In the Greenland case, we have used a more direct method to calculate the savings made by the users of the DMI services. This represents a direct cost linked to increased fuel and labour coupled with an opportunity cost where the ship is unavailable for other services (due to a longer sailing time in the absence of the DMI service). These benefits are combined into the one calculation for each user.

Since the ice-mapping services are mainly depending on the use of Sentinel data, we do not try to make a distinction to assign a partial value to the use of other satellite data – although there will be a small fraction. To do so would require us to assign some marginal value to an improvement in the quality of the service as each additional data source is taken into account. Whilst this could be done, it is beyond the scope of our work here and we leave for future researchers! In any case, we would estimate that this value for non-Sentinel data would be less than 10% and probably less than 5% of the total i.e. over 90% of the value is being driven by Sentinel's.

6.3 Widening the Perspective

This case is considered as being complementary to the Baltic even if some details differ; Greenland is unique in its situation. The same methodology could be applied to other ice-bound ports but in few cases will the dependence on the shipping be so high.

Alaska, Canada and Russia are countries with somewhat similar conditions as Greenland; but both have land transportation as well as shipping to transport goods. Only Canada extends as far into the polar region as does Greenland.

Russia is more interesting in the sense of the prospect of a northern passage for shipping between Europe, US and Japan. Global warming may open this as a route, but icebreakers will be a necessity. The use of satellite ice-mapping services to guide them will be of strong value.

6.4 Final Thoughts

Greenland is a really, interesting "country"!

As well as its strategic position between the US and Europe/Russia, Greenland sits at one of the cruxes of the climate change debate. As global warming continues, the ice sheet has been shown

to be melting with potential catastrophic effects. Around the coast, the reduced sea-ice is raising expectation of faster economic growth through more mineral extraction, tourism, fisheries and maybe off-shore exploration (not considered in this case).

There are few such clear situations where the economy depends on one industry (the shipping of goods) and that this industry benefits directly from the use of satellite data. Even the potential to offer better, more-timely services can impact directly on the growth of the country.

In our analysis, we have assigned an almost arbitrary value to the strategic benefit, but in many ways, this may be considered a low estimation. The whole of the Greenland economy benefits from the use of the DMI ice-mapping services and the Danish investment in their share of Copernicus seems to offer a very positive return on investment.

Annex 1: References and Sources

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Annex 2: General Approach and Methodology

This is the sixth case to be analysed which looks at the value being created by the use of Sentinel data. It follows the same basic methodology[40], established during a previous study, which follows a value chain for the use of a single EO service. Additionally, the analysis includes a look at the environmental impacts.

For each case, a value chain is established with a service provider and a primary user. The value-chain is validated with these two key players. Through a combination of desk and field research we develop our understanding of all the actors in the value chain, the role that they play and how they may benefit through the use of the satellite-derived products.

Once written, the draft report is then shared with all the persons with whom we have spoken and their comments are incorporated or a further discussion is held to establish common understanding. At the end of this process, the report is made public.

For each new case, a comparison of details of the methodology which has been used will update our perspective on the overall methodology to be used for future cases. What have we learned from this case?

In this case the following points stand out:

- This is the first case which has been treated as "complementary". In other words, it has similarities with a previous case which has been analysed; in this instance the case of "Winter Navigation in the Baltic[4]".
- Nevertheless, there are significant differences at the heart of the case which are highlighted through the report.
- There is a strategic value to the use of the ice-mapping service. This is due to the nature of the location in Greenland; this was also true in the Baltic where the towns to the North could only have developed in the way they have with the assistance of the ice-breaker services. In the Baltic, we dealt with the strategic value through a "willingness to pay" whilst here we do not consider this to be valid. Nevertheless, the value per citizen is compared to show a similar "benefit valuation".
- The main benefit is calculated through a mix of "opportunity cost" i.e. the daily cost of a ship which, due to delays caused by the ice, is not available for effective duty elsewhere, and the direct cost of additional fuel to make a longer journey without the information coming from the ice-charts.

[40] SeBS Methodology; June 2017.

Annex 3: Winners… and losers?

The creation and subsequent usage of Sentinel data down the value chain has a significant economic impact. Quite prominently, product and process innovation based on the availability and subsequent application of the data, lead to positive effects where new products and services emerge and existing processes can be run more effectively and efficiently. Conversely of course, there are also consequences on some of the previous beneficiaries. For instance, revenues might be shifted and jobs displaced and sometimes even destroyed, creating technological unemployment. In the current study, for example, some workforce might have been lost in reducing the site inspections while savings from farmers certainly translates into loss of revenues for the agro-chemical industry.

> As we have shown in our study 'Winter navigation in the Baltics' as the captains on the icebreakers in the Baltics could suddenly rely on Sentinel based ice charts providing a fully synoptic picture of the ice, the helicopter pilots they traditionally relied upon, became abundant.[41] Similarly, in our study 'Forest Management in Sweden' the Swedish Forest Agency could reduce the number of forest inspectors, as Sentinel data allowed for a reduction of in situ inspections.[42]

How technological progress and innovation are related to employment has been an area of fierce debate for centuries. From fairly recent studies appear that product innovation spark new economic activities, creating new sectors, more jobs, whereas process innovation[43] is more job destroying, although market mechanisms can sometimes largely compensate for the direct job losses, mitigating the ultimate impact on demand for labour. Such price and income compensations can derive from a decrease in wages, leading to an increase in demand for labour or the effects of new investments (enabled by accumulated savings) creating new jobs elsewhere. Obviously, the speed and impact of such effects are highly dependent on the flexibility of markets, the level of competition, demand elasticity, the extent of substitutability between capital and labour and, of course, possible institutional rigidity.[44]

> A German study on the co-evolution of R&D expenditures, patents, and employment in four manufacturing sectors concluded that patents and employment are positively and significantly correlated in two high-tech sectors (medical and optical equipment and electrics and electronics) but not in the other two more traditional sectors (chemicals and transport equipment).[45] Similarly, a study using a panel database covering 677 European manufacturing and service firms over 19 years

[41] Sawyer, G. and De Vries, M. "Winter navigation in the Baltic." Copernicus Sentinels' Products Economic Value: A Case Study (2015)

[42] Sawyer, G. and De Vries, M. "Forest Management in Sweden." Copernicus Sentinels' Products Economic Value: A Case Study (2016)

[43] As process innovation is defined as producing the same amount of output with less labour (and sometimes other) inputs, logically the direct impact of process innovation is job destruction when output is fixed.

[44] Vivarelli, M. "Innovation and employment: Technological unemployment is not inevitable—some innovation creates jobs, and some job destruction can be avoided." IZA World of Labor 2015: 154

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(1990–2008) detected a positive and significant employment impact of R&D expenditures only in services and high-tech manufacturing but not in the more traditional manufacturing sectors.[46] Another study found a small but significant positive link between a firm's gross investment in innovation and its employment based on longitudinal data set of 575 Italian manufacturing firms over 1992–1997.[47]

Clearly, this tells us that the ultimate 'net' impact of innovation – both at product and process level - brought about by the availability of new technology, such as Sentinel data, will be closely related to the market and institutional settings in which they become effective. However, on the whole the conclusion seems justified that the 'negative' effects, in the form of possible loss of employment, is largely outweighed by the positive economic effects throughout the value chain.

Accordingly, in this study – and likewise for the past and future ones - we will concentrate on the positive effects brought about by the availability of the Sentinel data throughout the value chain. That there are also (temporary) 'negative' impacts is a given, but the net effect at macro level will always be positive.

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