Integrated Arctic Observation System

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1	NERSC		**24**	Terradue	
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3	IMR		**26**	UNEXE	
4	MISU	***0,5***	**27**	NIVA	
5	AWI	***0,5***	**28**	CNRS	
6	IOPAN		**29**	U Helsinki	
7	DTU		**30**	GFZ	
8	AU		**31**	ARMINE	
9	GEUS	***0,5***	**32**	IGPAN	
10	FMI		**33**	U SLASKI	
11	UNIS		**34**	BSC	
12	NORDECO	***0,5***	**35**	DNV GL	
13	SMHI		**36**	RIHMI-WDC	
14	USFD	***0,5***	**37**	NIERSC	
15	NUIM		**38**	WHOI	
16	IFREMER		**39**	SIO	
17	MPG		**40**	UAF	
18	EUROGOOS	***1,0***	**41**	U Laval	
19	EUROCEAN		**42**	ONC	
20	UPM		**43**	NMEFC	
21	UB	***1,0***	**44**	RADI	
22	UHAM		**45**	KOPRI	
23	NORUT		**46**	NIPR	
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DISSEMINATION LEVEL		
PU	Public, fully open	X
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CI	Classified, information as referred to in Commission Decision 2001/844/EC	

EXECUTIVE SUMMARY

The detailed analysis of phenomena and observation requirements for the Arctic region given in this report reveals the following conclusions:

- The Arctic is a region very sensitive to environmental changes. There is a very close interrelation and delicate balance between the five thematic areas investigated (atmosphere, terrestrial, cryosphere, sea ice and ocean), especially in relation to solar energy and radiation budget and hydrological cycle. This has a great impact on physical, chemical and biological processes in the area.
- Due to the hostile environment, there is a great lack of basic observations in the Arctic, that can support scientific understanding of key processes. Most of the existing data are collected via time limited research projects. This lack of process knowledge is reflected in big errors in forecasting models – operational as well as climate.
- It is therefore crucial to establish a sustained Integrated Arctic Observing System, that in the short timeframe can increase fundamental scientific understanding of the complex and sensitive Arctic environment and in a longer timeframe can secure a robust basis for decision making to the benefit of the people living in the Arctic, the environment, the broader international society, and commercial activities.
- It is foreseen that a future Arctic observation system will rely heavily on satellite observations supplemented by more traditional in-situ platforms. Especially the ocean will use several other platforms such as ships, profiling floats, gliders, moorings, AUV’s etc. to monitor the interior of the Arctic Ocean.
- In all countries around the Arctic, there are community based observing systems that represent a strong potential for further development. Existing activities shall form part of the natural basis for a future more intensive and integrated sustainable Arctic Observing System.
- A stakeholder workshop was held in Brussel on 5 May, organised by EuroGOOS, where status and challenges regarding development of Arctic Observing Systems were discussed. In addition to technical and logistical challenges, there are also organisational barriers to building and operating a multidisciplinary observing system. These issues will be addressed in follow-up workshops.

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1. INTRODUCTION

It is internationally agreed that (UNESCO, 2010):
"The Arctic Region is warming at roughly twice the global average rate, with a dramatic reduction in summer sea ice extent as one of the clearest indicators of this trend. Physical and biological processes are being transformed across the entire region, while climate feedback mechanisms in the Arctic's changing atmospheric and oceanic dynamics impact at global scales.

Change in the Arctic environment is also leading to a wealth of interconnected social transformations. Arctic states dispute territorial claims as the Arctic reveals its increasing economic and strategic potential, while the international community also seeks to have a voice and a guaranteed research presence in the region. The oil and gas industry is sizing up the arctic sea bed for exploitation, and economically important shipping lanes are predicted to open. With industrial development, increasing numbers of people are migrating to the Arctic. The region's indigenous peoples are stepping up their efforts to gain control over the developments taking place in their territories, while maintaining their cultural continuity. Meanwhile, conservationists are increasingly highlighting the need to protect the fragile arctic environment.

Vulnerability in the Arctic Ocean is therefore increasing. Its environment and peoples are under growing stress from climate change. Industrial infrastructure and shipping create further pressures, while simultaneously being at risk themselves in this often-hostile region.

Never has accurate information been more important, yet at present we know very little about the Arctic Region. Critical physical processes are poorly understood, ecosystems remain unstudied and undiscovered, and indigenous voices go unheard. This lack of knowledge thwarts efforts to detect, predict or manage the interrelated physical, biological and social impacts of climate change, making sustainable development almost impossible. A coordinated and sustained observing system must therefore be created for the Arctic Region, to provide baseline data and ensure sustained monitoring.

But what should such a system look like? To be sustained in the long term, an Arctic Observing System must move beyond academic research. It must respond increasingly to 'user pull', providing products and services of direct utility to the burgeoning number of stakeholders in the region".

To address these tremendous challenges the EU Horizon 2020 Programme has funded the INTAROS project, with the overall objective to build an efficient integrated Arctic Observation System (iAOS) by extending, improving and unifying existing systems in the different regions of the Arctic. This overall objective is translated into 9 specific objectives:

1. Establish a Pan-Arctic forum to support formulation of agreements and collaboration between organization involved in developing Arctic observing systems across EU member states, non-EU countries and transnational organizations
2. Develop a Roadmap for future implementation of a Sustainable Arctic Observing System (SAOS).
3. Exploit existing observing systems and databases of atmosphere, ocean, cryosphere, geosphere and terrestrial data as the backbone of an integrated Arctic Observing System (iAOS) platform
4. Contribute to fill gaps of the in situ observing system by use of robust technologies suitable for the Arctic.
5. Add value to observations through assimilation into models.
6. Enhance community-based observing programmes by building capacity of scientists and community members to participate in community based research
7. Develop and implement the iAOS platform for integration and analysis of multidisciplinary

with distributed data repositories.
8. Demonstrate benefit of the iAOS functionality to selected stakeholders.
9. Develop professional skills in using the iAOS platform and new data products within industry, education and science.

To determine an adequate Arctic observing strategy, the observing objective needs to be defined first. Observing objectives for sustained observing should address one or more societal relevant needs which could be for example a routine product that informs society about the status of a part of the Arctic but which may ultimately ask for a decision to be taken. This process involves close interactions with relevant stakeholder groups.

Although the Arctic Observing System that INTAROS aim to design includes atmosphere, land, cryosphere, sea ice and ocean, it has been decided in this "Initial Requirement Report" to follow the design philosophy outlined in *"Framework for Ocean Observations (UNESCO, 2012)"*, which also was followed in the AtlantOS project. It is focused on a systems approach:

- delivering a system based on common requirements, coordinated observing elements, and common data and information streams,
- using "Essential Variables" as a common focus for requirements, defined based on *feasibility* and *impact* on societal and scientific drivers, and
- evaluation of "readiness levels" for each of these system components.

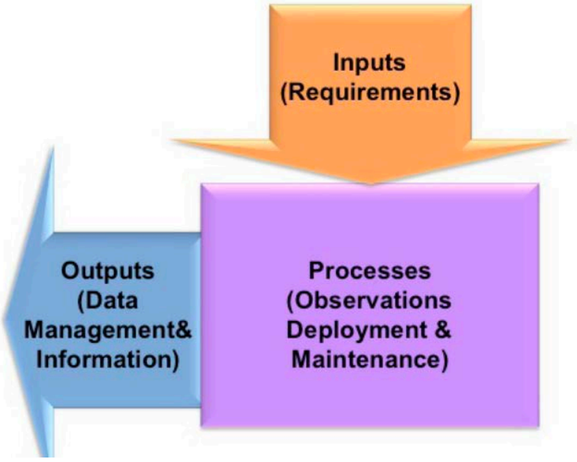


Figure 1-1 A simplified representation of the basic system design

After defining the observing objective for sustained observing system a set of relevant phenomena and essential variables, but considering the regional context, will emerge. The phenomena assist in determining time and space scales over which the observing is to be executed. The phenomena also narrow down the essential variables that belong to the observing objective. From the combination of phenomena and Essential Variables the set of suitable observing platforms and sensors emerge. This "selection" is, *per-se,* a predefined process because observing platform have only limited/known time/space/sensor potential.

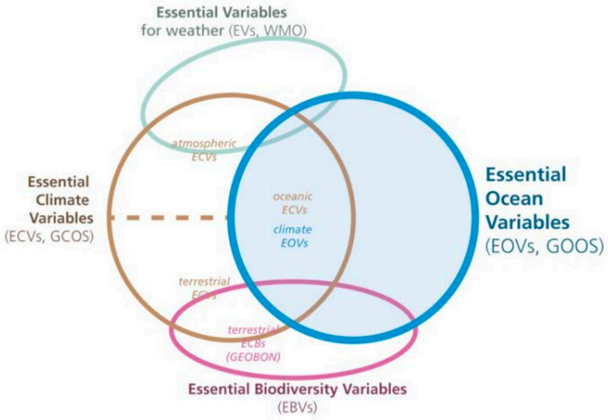


Figure 1-2 Link between Essential variables defined by the WMO for weather forecasting, Essential Climate Variables defined by GCOS, Essential Biodiversity Variables defined by GEOBOB and Essential Ocean Variables defined by GOOS

Talking here about a multiplatform, multidisciplinary Arctic wide system, the observing process is seamless for the many observing objectives it is in place for. That means the data collected by the observing platforms is used for many different observing objectives. The capacity of the sustained observing system defines the ability to deliver information that can serve additional observing objectives. Likewise, the gaps of the sustained observing system are defined by the observations (time/space/sensor) that are not available to inform society sufficiently in respect to a certain observing objective. The gaps can be results of new observing objectives that require new sampling (time/space/sensor), but can also be the gaps from a degradation of the system or the lack of open and free data sharing.

In general, according to the Framework for Ocean Observations (UNESCO, 2012), the readiness of the integrated observing system is measured across three components:

1) an understanding of the requirements of the integrated observing system (i.e., the Essential Variables needed to meet the observing objectives);
2) the ability to make observations with sufficient accuracy on the required time and spatial scales (which depends on technology, funding, and cooperation among observing networks); and
3) data analysis, data management, and the provision of ocean information to users in timely fashion (which includes common standards, as well as free and open access to data).

Along each of these three dimensions, the readiness of the observing system evolves from concept through pilot to mature with rigorous review, vetting, and approval by the community to allow for innovation while protecting against inadequate or duplicative solutions.

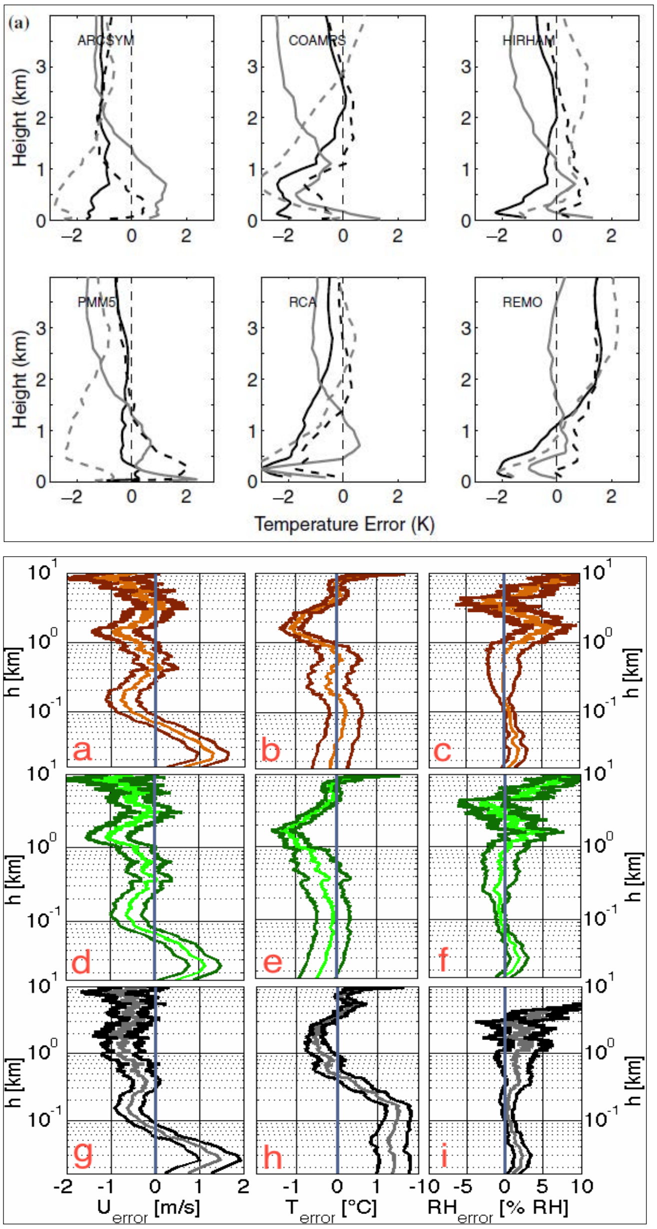
The present analysis of phenomena, requirements, essential variables and observing technology has logically been split into atmosphere, terrestrial, cryosphere, sea ice and ocean very well knowing that these are strongly interconnected but also have different level of maturity in scientific understanding of the phenomena, definition of essential variables and observation capability.

In recent years, alternative monitoring approaches have emerged, where community members are directly involved in data collection and interpretation. When properly designed and carefully tailored to local issues, such community-based observing systems can provide valuable data, cost-effectively and sustainably, while simultaneously building capacity among local constituents and prompting practical and effective management interventions. In the last chapter of this report, we discuss the potentials and challenges of community-based observing systems in the Arctic.

2. IMPORTANT PHENOMENA AND HOT SPOTS

2.1 ATMOSPHERE

Numerical models exhibit rather large systematic errors in the Arctic atmosphere, when evaluated against field experiment data from expeditions to the Arctic; a few examples will be provided below.



Figur 2-1 *Errors in vertical profiles in (top) six regional models using SHEBA observations (Tjernström et al. 2005), and (bottom) in different reanalysis products (Wesslén et al. 2014) using observations from ASCOS. The top panel shows seasonal mean temperature error; autumn and winter in solid black and grey lines, respectively, and spring and summer in dashed black and grey lines, respectively. The bottom panels show wind speed, temperature and humidity errors for two versions of the Arctic System Reanalysis (a-c and d-f) and for ERA-Interim (g-i). Here the error is expressed as the median error (central lines) and the 5th and 95th percentiles.*

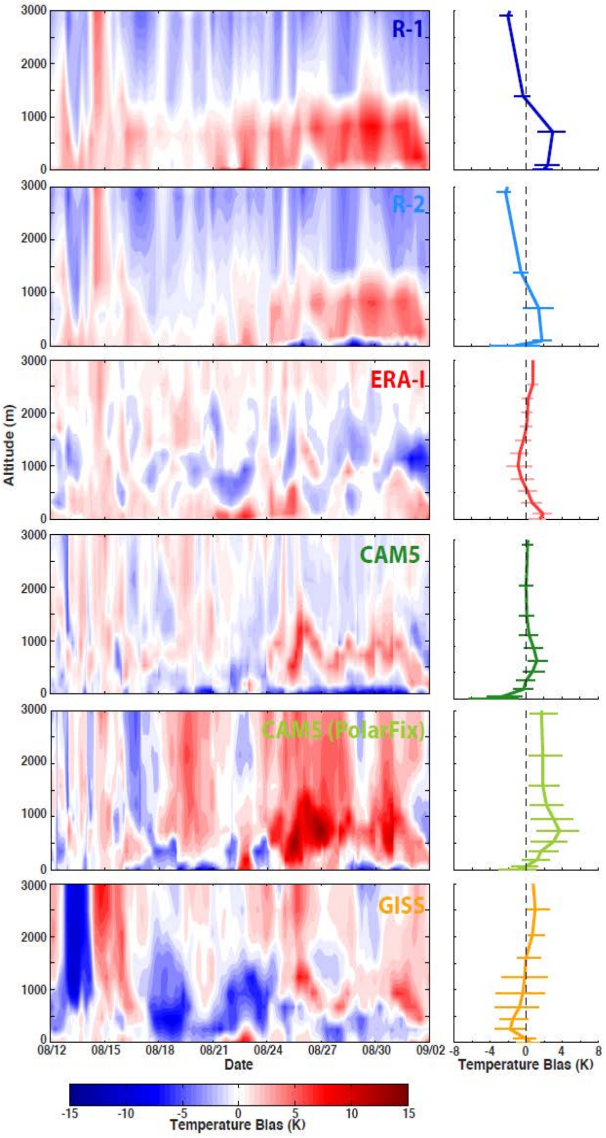


Figure 2.1 Time-height cross-sections of temperature error (left) and time mean temperature bias (right) for several climate models and ERA-Interim, comparing to soundings **from a three-week ice-drift during ASCOS (from de Boer et al. 2014).**

Arguably, these errors are due to a lack of observations in two ways. First, parameterizations in numerical models are resting on field experiments with detailed information at the process level, of which there are substantially less in the Arctic than in other climate zones. To the extent that climatology is different in the Arctic such that processes behaves differently, or that the ensemble of processes covers different domains, lack of process-level observations prohibits model development. Second, forecasting on all time scales and reanalysis requires observations to keep systematic model errors from developing. In this section, we will address three thematic areas where this problem is especially large: The vertical structure of the troposphere, clouds and related aerosols, and surface energy fluxes. We will also address a “hot spot”; seasonal and marginal sea-ice zones.

Vertical thermodynamic structure of the troposphere

Observing and understanding the vertical structure of the atmosphere lies at the heart of both forecasting and climate monitoring. It entails several important aspects such as vertical stability, which affects the development of cyclones and anticyclones, and vertical energy fluxes and clouds; the largest modulator of the local and regional energy fluxes in the Arctic atmosphere. The vertical structure is determined by a combination of transport of air masses from southerly latitudes, energy fluxes at the surface and the top of the atmosphere, and by small-scale physical processes in the atmosphere, most notably by clouds and their effect on radiation (see below).

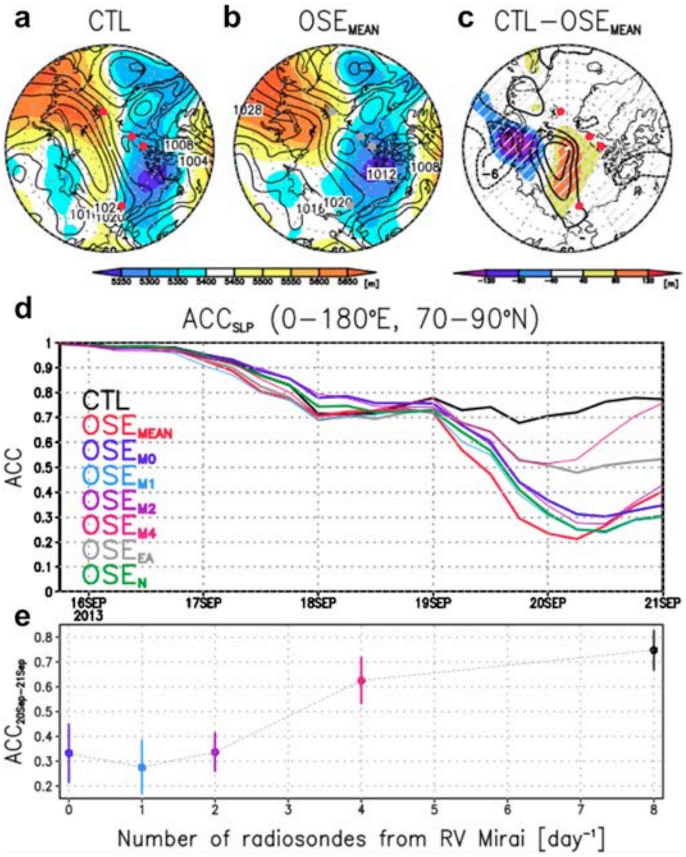


Figure 2-3 *Five-day forecasts of Z500 (shading) and SLP (contours) in the (a) CTL and (b) OSE experiment and (c) their difference, (d) the anomaly correlation (ACC) for each ensemble mean forecast, and (e) ACC as a function of the number of radiosondes from RV Mirai (from Inue et al. 2015).*

Errors in correctly describing the vertical structure of the atmosphere in models have been evaluated mainly against observations from field expeditions into the Arctic. Tjernström et al. (2005) compared six different regional models to observations from the year-long SHEBA expedition (*Figure 2.1* upper panel). Systematic errors in temperature, here expressed as three-month averages, spans ±2 K, is typically the largest in the lowest 1-2 km of the atmosphere and is different for different models although all the regional models were forced at the lateral boundaries by the same large-scale analyses from the European Centre for Medium-range Weather Forecasts (ECMWF) operational suite. Corresponding specific-humidity errors showed a similar vertical structure, while wind-speed errors were typically ±2 m s^{-1} (not shown). The errors in the lowest 1-2 km are likely due to unrealistic clouds and atmospheric boundary-layer turbulence descriptions. Wesslén et al. (2014) similarly evaluated errors in three reanalysis products (*Figure 2.1* lower panel) using observations from the 40-day Arctic Summer Cloud-Ocean Study (ASCOS; Tjernström et al. 2014, also see Figure 3-3) expedition during the latest International Polar Year (IPY). All three displays systematically to low wind speeds in the free troposphere (above the boundary layer) and too high winds closer to the surface. ERA-Interim (Dee et al. 2011) has a pronounced boundary-layer warm bias, while all three reanalysis products have a mid-tropospheric cold bias with a collocated moist bias. All reanalyses also have large errors in the vertical position of the tropopause, indicated by increasing temperature errors approaching the tropopause. de Boer et al. (2014) performed a similar analysis for a set of climate models, focusing on the three-week ASCOS ice drift. *Figure 2.1* shows the temporal and vertical temperature errors with averaged error profiles for each climate model to the right. While the three-week average error is most often largest in the lowest kilometre, at ± ~3 K, local temperature errors span as much as ± 15 K.

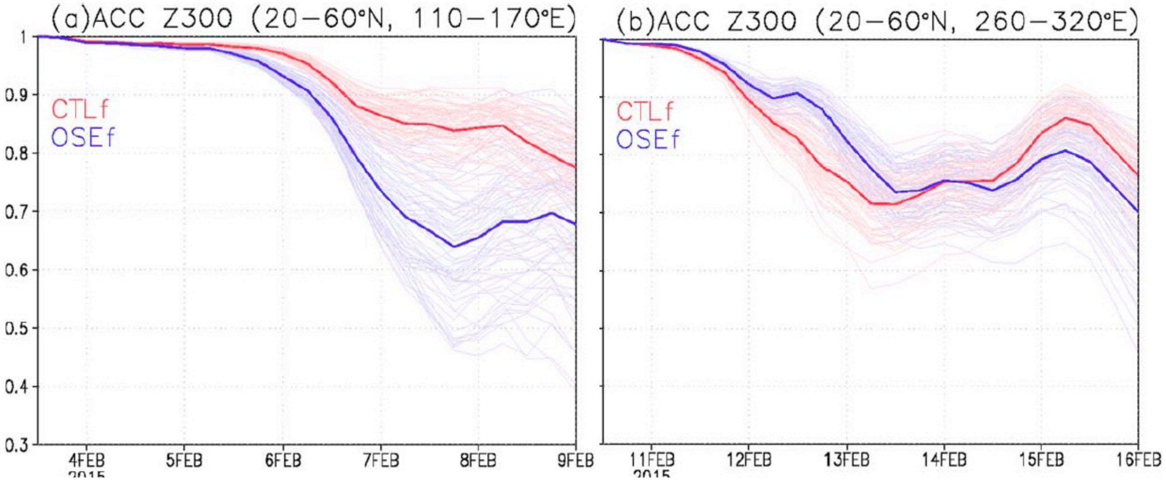


Figure 2-4 ***300 hPa anomaly correlations for two ensemble forecast experiments, with (red) and without (blue) extra soundings from N-ICE, showing all members (thin lines) and ensemble averages (thick lines) for (a) East Asia and (b) North America (from Sato et al. 2016).***

Accurate information on the vertical structure of the atmosphere has a large impact on the quality of weather forecasting. Inoue et al. (2015) reports on a numerical modelling experiments from the summer of 2014, when additional soundings were available at four different locations: at Ny-Ålesund on Svalbard, Alert and Eureka in northeast Canada, and on the RV Mirai navigating in the marginal ice zone north of the Bering Strait. Running a 63-member ensemble forecasting data-assimilation system and systematically including or excluding the extra sounding stations, it is clear that the five-day forecast changed substantially while excluding the four extra soundings (Figure 2.3a-c); note especially the remote signature indicating that the information from the soundings propagated to have an impact also in areas far away from where the observations were made. Figure 2.3d shows the sea-level pressure anomaly correlation for the different experiments. The control simulation, including all the extra soundings, performs the best and the experiment denying all the extra soundings had the poorest performance. Differences starts to appear after 24 hours and grow rapidly after three days. Interestingly, there is a large average performance increase going from two daily soundings to four; doubling once more to eight soundings per day, however, did not buy such a large improvement. Most importantly, the information from soundings of the vertical structure in the Arctic propagates far. Sato et al. (2016) carried out similar forecast experiments, but using the soundings from the Norwegian young sea ICE expedition (N-ICE; Granskog et al., 2016) in 2015. Evaluating this impact in different mid-latitude sectors it was found that the impact on the ensemble forecast depended on the weather situation. One example, from a cold-air outbreak, shows a significant improvement in the 300 hPa geopotential field for East Asia, but no significant impact for North America (Figure 2-4).

Clouds and cloud properties, including aerosols

Clouds remain the largest uncertainty in climate modelling and are also an important component in weather forecasting on all time scales. The importance of clouds stems from their interactions with electromagnetic radiation. They reflect shortwave (SW) solar radiation to space but also has a "greenhouse effect", warming the surface by absorbing and emitting infrared longwave (LW) radiation. The effects at the top of the atmosphere depends strongly on location of the clouds and on the cloud microphysics. Besides the lack of relevant observations, three aspects sets clouds in the

Arctic apart from at other locations: 1) The strong annual cycle, with a long polar night; 2) The preponderance of high surface albedo over snow and ice; 3) The remote location, leading to a different aerosol climate than elsewhere.

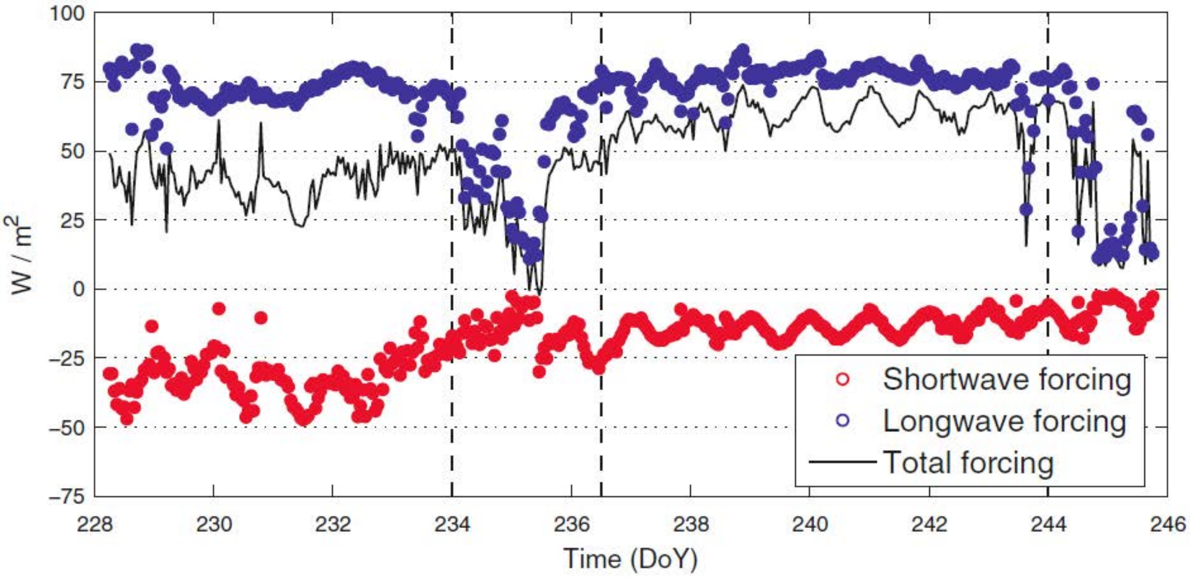


Figure 2-5 Time series of the surface cloud radiative effects in SW (Red), LW (blue) and net (black), from the three week ASCOS ice drift (from Sedlar et al. 2011)

During the polar night, SW radiation is largely absent and hence the LW radiation dominates. LW radiation is very sensitive to cloud water phase, liquid being much more efficient than ice. One of the main lessons from the Surface Heat Budget of the Arctic Ocean experiment (SHEBA, Uttal et al,2002) was the existence of liquid water in low-level clouds even at temperature down below -40 °C. Hence in winter, LW radiation dominates the effects of the clouds and cloudy conditions typically means less cold conditions and a shallow and well-mixed layer close to the surface, while clear conditions means colder temperatures and a strong static stability. This is because with clouds, the surface effectively radiating energy to space is shifted from the surface to the cloud top. The cloud top then cools generating buoyancy by “up-side-down convection” and hence mixing. During SHEBA this conditions occurred about half the time (Tjernström and Graversen 2009).

In summer the conditions are different, with the presence of SW radiation. Still, if the surface albedo is sufficiently high, the presence of clouds make little difference for the net radiation since the albedo of clouds and surface may be similar. Hence, less clouds means more SW radiation reaching the surface, but also less LW radiation; if the surface albedo is sufficiently high, LW wins out and the net radiation at the surface decreases with a cloud reduction. The effects of clouds on the radiation balance is often expressed as the “cloud radiation effect” or CRE; the part of the net radiation due to the clouds This is illustrated in Figure 2-5, from the ASCOS expedition. Time periods when the cloud cover partially or completely breaks up are DoY (day of the Year) 234 – 236.5 and after DoY 244. In between those, the surface $\mathrm{CRE}_{\mathrm{LW}}$ is typically ~75 W m^{-2}, but when the clouds disappear it drops to close to zero. Any similar response in the $\mathrm{CRE}_{\mathrm{SW}}$ remains small; before DoY 234 the $\mathrm{CRE}_{\mathrm{SW}}$ is -30 - -40 W m^{-2} and after DoY 237 it is reduced to -10 - -20 W m^{-2}. The reason for the change in $\mathrm{CRE}_{\mathrm{SW}}$ is due to a change is surface albedo partly from riming on the surface and partly from new snow from frontal systems passing both around DoY 234.0 and 236.0. Even before DoY 234, losing the clouds increases the net SW radiation by only 20-40 W m^{-2}, while simultaneously reducing the net LW radiation by ~75 W m^{-2}; hence the surface loses ~40 W m^{-2} and the surface temperature drops (not shown). The $\mathrm{CRE}_{\mathrm{LW}}$ is typically a function of the integrated liquid cloud water (or LWP) while the $\mathrm{CRE}_{\mathrm{SW}}$ is also dependent on surface albedo and solar zenith angle; for the case in Figure 2-5, it is the largest negative, ~ -45 W m^{-2}, at the lowest surface albedos ~70% and at the smallest zenith angles, ~75° (not shown).

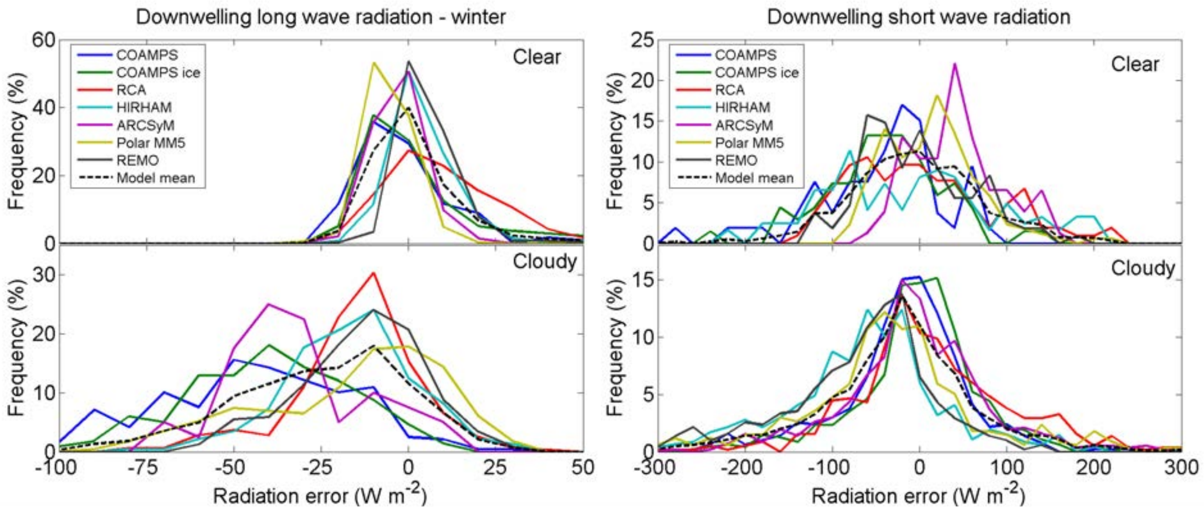
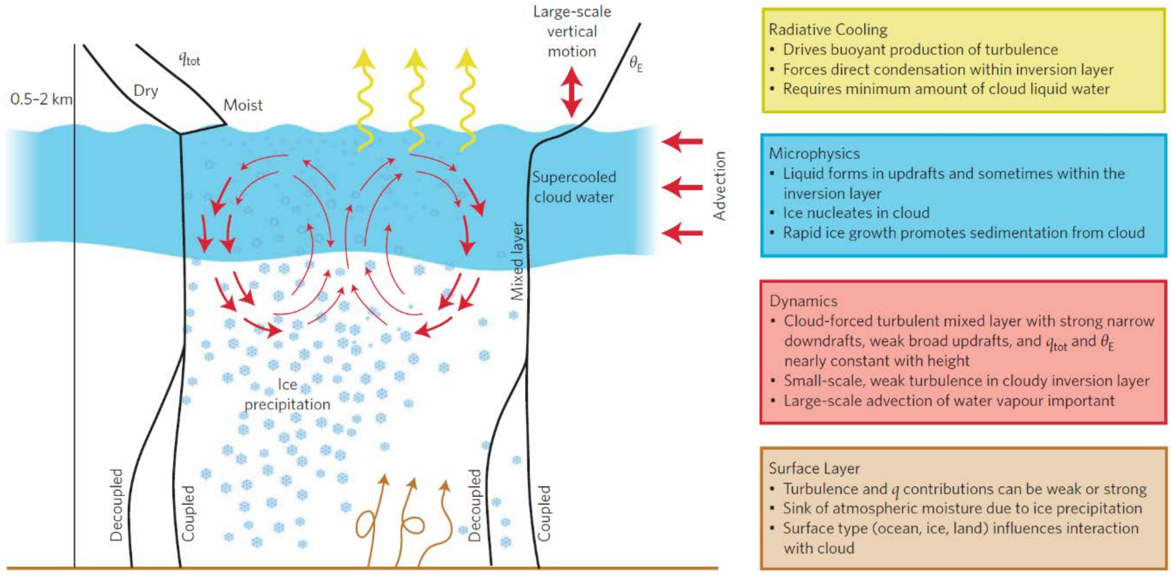


Figure 2-6 Examples of errors in incoming radiation in several regional models comparing to the SHEBA observations, from Tjernström et al. (2008) using PDFs. Left to panels show longwave radiation for winter and right two panels show shortwave radiation in summer, while the two upper panels show cloud free and the lower cloudy conditions.

Due to the sensitivity on the specific micro-physical details, model struggle to get this right, which is illustrated in Figure 2-6. Shown here is an analysis of downwelling radiation in several regional models, the same models as in Tjernström et al. (2005), from Tjernström et al. (2008); downwelling radiation was selected, rather tan net radiation, to exclude problems with surface temperature or albedo in the models. For LW radiation in winter, model errors are reasonably small for clear conditions but very large and skewed towards large negative values for cloudy conditions. Most of this error is due to the models preferring ice clouds rather than the observed liquid clouds. For SW radiation in summer the errors for cloudy or clear conditions are similar in magnitude and are mostly due to the model's inability to correctly model the presence of clouds, but it is noteworthy that the peak errors are somewhat negative. This indicates that the clouds are somewhat to optically thick; the cloud albedo is to large.



Radiative Cooling
- Drives buoyant production of turbulence
- Forces direct condensation within inversion layer
- Requires minimum amount of cloud liquid water

Microphysics
- Liquid forms in updrafts and sometimes within the inversion layer
- Ice nucleates in cloud
- Rapid ice growth promotes sedimentation from cloud

Dynamics
- Cloud-forced turbulent mixed layer with strong narrow downdrafts, weak broad updrafts, and q_{tot} and θ_E nearly constant with height
- Small-scale, weak turbulence in cloudy inversion layer
- Large-scale advection of water vapour important

Surface Layer
- Turbulence and q contributions can be weak or strong
- Sink of atmospheric moisture due to ice precipitation
- Surface type (ocean, ice, land) influences interaction with cloud

Figure 2-7 Illustration of a conceptual model highlighting the primary processes and basic physical structure of persistent Arctic mixed-phase clouds (from Morrison et al. 2012).

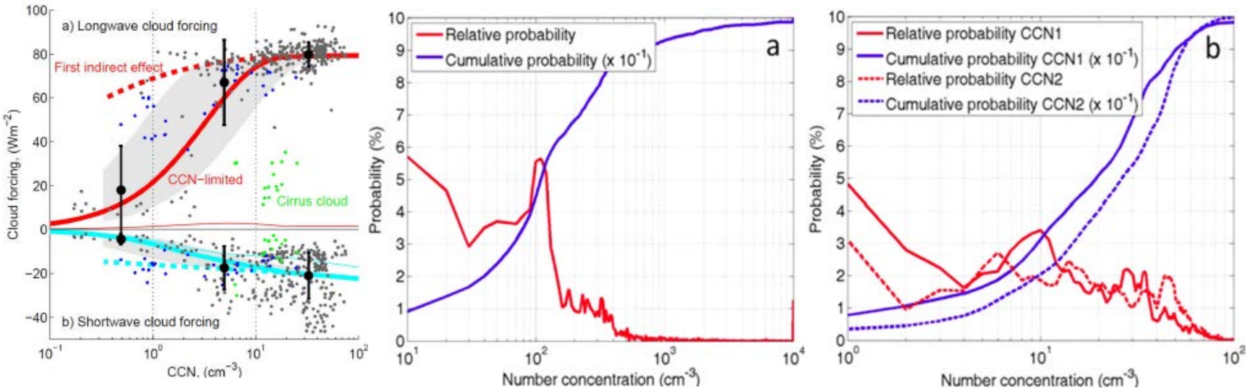


Figure 2-8 Aerosol/cloud interactions during ASCOS, shown by (left) the surface cloud radiative effect as a function of CCN concentration (from Mauritsen et al. 2011), (middle and right, respectively) PDFs of total aerosol and CCN concentration (from Tjernström et al. 2014).

The optical thickness of the clouds is a key parameter and very difficult to observe. While the formation of clouds is due to the meteorological situation, the optical properties of the clouds are also strongly affected by the prevalent aerosol conditions. It has been understood for a while that the existence of liquid water at low temperatures (e.g. Prenni et al. 2007) is due to the low number of ice forming nuclei (IFN); aerosol particles on which liquid droplets can freeze. Low-level mixed-phase clouds, where a thin liquid layer semi-continuously shed ice particles, are very frequent in the Arctic (Shupe 2011) and in contrast to more southerly latitudes, they are also very persistent (Shupe et al. 2011). Morrison et al. (2012) provide a review of important processes for the resilience of this type of clouds, see Figure 2-7. One of the important processes here is the formation of liquid droplets in the cloud-driven updrafts followed by the subsequent formation and growth of ice crystals falling out of the liquid layer. This is very sensitive to the number of IFN present; too efficient ice formation and the liquid layer will be drained and the cloud will dissipate. Liquid droplet formation on the other hand requires presence of cloud condensation nuclei (CCN); more CCN will lead to more and consequently smaller droplets, while insufficient number of CCN will prohibit cloud formation. Birch et al (2012 used the UK Unified Model and specified the CCN concentration, and showed that only when specified as low as observed could the observed dissipation of a cloud layer be modelled.

Concurrent observations of aerosols and clouds during ASCOS illustrates this importance. Mauritsen et al. (2011) describes a case where the CCN concentrations dropped so low that it inhibited cloud formation, with subsequent effect of the surface energy balance and surface temperatures. They then generalize all observations from ASCOS and concluded that there are two regimes; one CCN-sparse, at concentrations < 10 cm^{-3}, where an increase in CCN concentration warms the surface by gradually saturating the longwave radiation from clouds. At CCN concentrations > 10 cm^{-3}, the effect is the opposite by increasing the cloud albedo; see Figure 2-8. A synthesis of all aerosol observations during ASCOS in Tjernström et al. (2014) illustrates the special conditions in the central Arctic summer (Figure 2-8); the median total number concentrations of aerosols is very low, ~100 cm^{-3}, while the median CCN concentration is ~ 20-30 cm^{-3}; both values are substantially lower that corresponding typical mid-latitude values. Sotiropoulou et al. (2014) later determined from more indirect methods that optically thin clouds occurred about 30% of the time during ASCOS. However, whether the 2008 summer was typical for Arctic summer aerosol conditions is impossible to say.

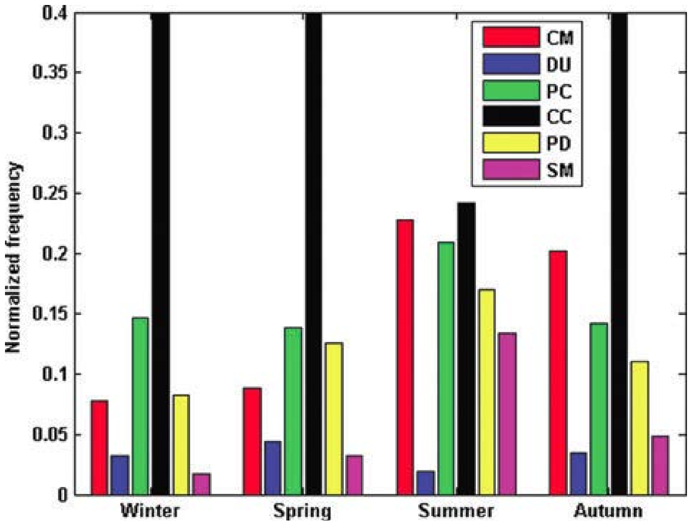


Figure 2-9 Relative frequency of occurrence of layers for six aerosol types in the latitude band between 67 and 82 °N. For each season, frequency of occurrence of each aerosol type is normalized by the total number of aerosol layer observations in that season. The aerosol types are: CM - clean marine; DU - dust; PC – polluted continental; CC - clean continental; PD - polluted dust and SM - smoke. The CC histograms peak at 0.64, 0.57 and 0.46, for winter, spring and autumn seasons, respectively.

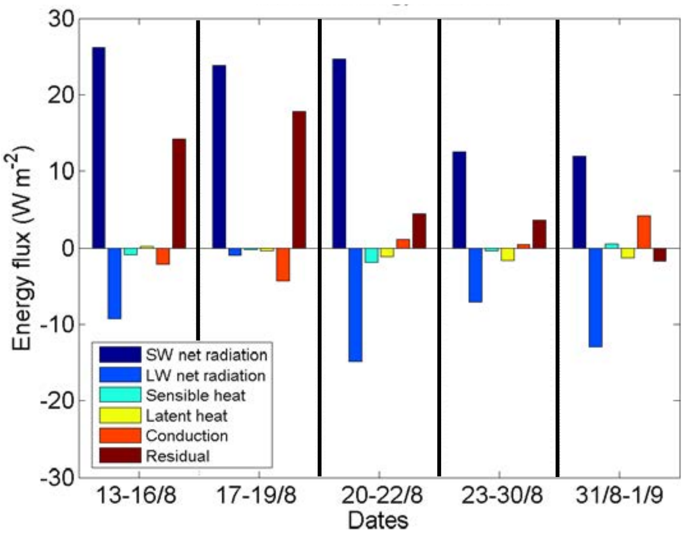


Figure 2-10 The terms in the surface energy budget from ASCOS (Sedlar et al. 2011) showing the transition from surface melt (two first time periods), to marginal conditions (next two), to freezing (last time period)

At some of the IASOA stations (e.g. at Barrow, Alaska), consistent cloud monitoring goes back a decade or two; for other IASOA stations it has started more recently (e.g. on Summit, Greenland, and Ny-Ålesund, Svalbard). Except for measurements on scientific expeditions, no detailed measurements of clouds or cloud properties in the central Arctic exist. The same is true for aerosol observations; several IASOA (or similar stations) have long-term observations of aerosols but except for scientific expeditions there are no direct observations in the central Arctic. To some degree, the advent of the so-called A-Train of satellites has revolutionized observations of clouds from space. Especially the active CloudSat (radar) and Calipso (lidar) sensors have had important applications. For the Arctic, however, this set of observations have two important limitations. First, the pencil-shaped patterns of the sensors is limited to south of ~82°N, and second, while the lidar is rapidly attenuated by clouds the radar has a lower limit around 400 m due to so-called ground-clutter. As Arctic clouds are dominated by low-level clouds, especially the latter implies a serious limitation. The lidar observations from Calipso also provides some information on aerosols occurrence and type; an example is provided in Figure 2-9.

The importance of monitoring changes in clouds and cloud properties, as well as the aerosols necessary for IFN and CCN production, follows from above discussion.

Surface energy budget

The surface energy budget (SEB) consists of the radiation fluxes (shortwave/solar and long-wave/thermal), the turbulent heat fluxes (sensible and latent), and the heat flux either in the soil or conducted through sea ice. The terrestrial SEB is observed at many of the IASOA stations and also at a large number of terrestrial stations, however, in the latter cases often as a side product, while trace fluxes (e.g. carbon dioxide or methane) are often the main motivation for these measurements. Many of these observations, especially from the terrestrial stations, suffer from lack of coordination and systematic calibration and evaluation. Over sea ice, and in summer the open ocean, there are essentially no such observations at all. Sea-ice freeze and melt are consequences of a surface energy imbalance; hence it follows that knowing this energy balance is key to understanding the changes in sea ice extent and concentration.

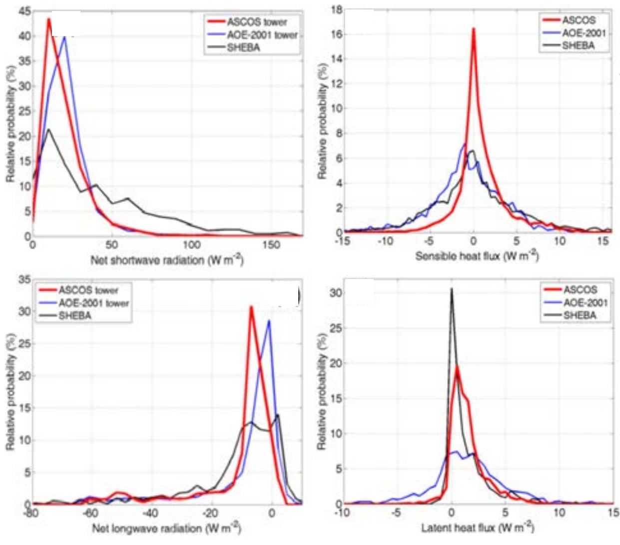


Figure 2-11 Probability function for the main components of the SEB, from three different summer research expeditions, from Tjernström et al. (2012).

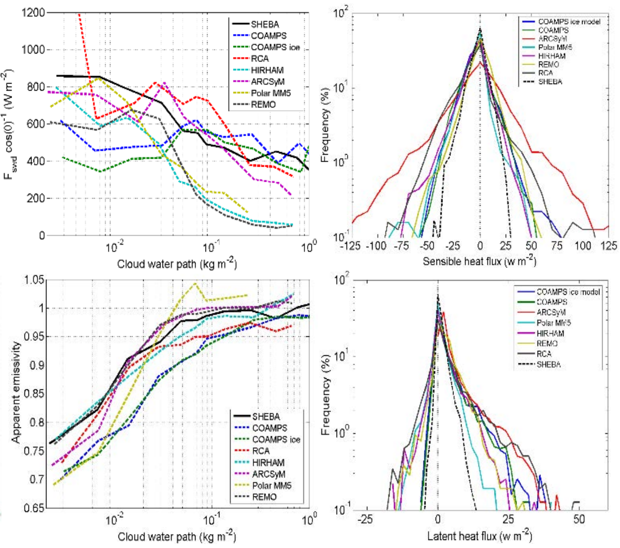


Figure 2-11 Modelling errors for components of the SEB, in (left) incoming radiation and (right) turbulent fluxes. The radiation plots show solar radiation and longwave emissivity as a function of cloud water path, from observations and models, while for the turbulence fluxes, models and observations are shown as probability functions*(modified from Tjernstrom et al, 2008*)

A few observations from research expeditions exist; an example is provided in Figure 2-10 from ASCOS, where all the terms in the SEB were observed. The sum of the fluxes in each time period (dark red) represents the energy available to melt ice. When positive ice is melting and whenever negative it is freezing. In this figure, the two first periods represent the end of the melt season, the next two a marginal period and the final period is the transition to the freeze up. Observations of fluxes from three expeditions that measured at least the radiative and turbulent heat fluxes are illustrated in Figure 2.11, as probability functions. The radiative fluxes are typically the largest; they also feature PDFs with long tails, associated with cloud-free conditions. The turbulent fluxes, on the other hand, are often close to zero, but varies within ± 5-10 W m^{-2}. Although smaller, the turbulent fluxes are still important. Not shown here are the turbulent momentum fluxes. These are responsible for how ice is forced to drift by the wind, and also for ridging and rafting of sea ice.

Models struggle to describe also the SEB, as illustrated in different ways in Figure 2-11. The two leftmost panels focus on incoming radiation from the atmosphere, to avoid contamination by simultaneous errors in surface temperature and albedo, and show the incoming radiation as a function of cloud water; note how most model results lie below the observed function, hence providing too little radiation to the surface. For the turbulent fluxes, as described by their PDFs in observations and models; note how the model PDFs are anywhere from 2-5 times wider than in the observations, indicating that the modelled fluxes are much too large, regardless of sign.

Marginal and seasonal ice zones

The portion of the Arctic Ocean that opens up in summer and the adjacent marginal ice zone is an emerging "hot spot" where essentially no observations are available. It is an area where sea ice melts and is formed, and to understand these processes better integrated interdisciplinary observations of the upper ocean and the lower atmosphere is required.

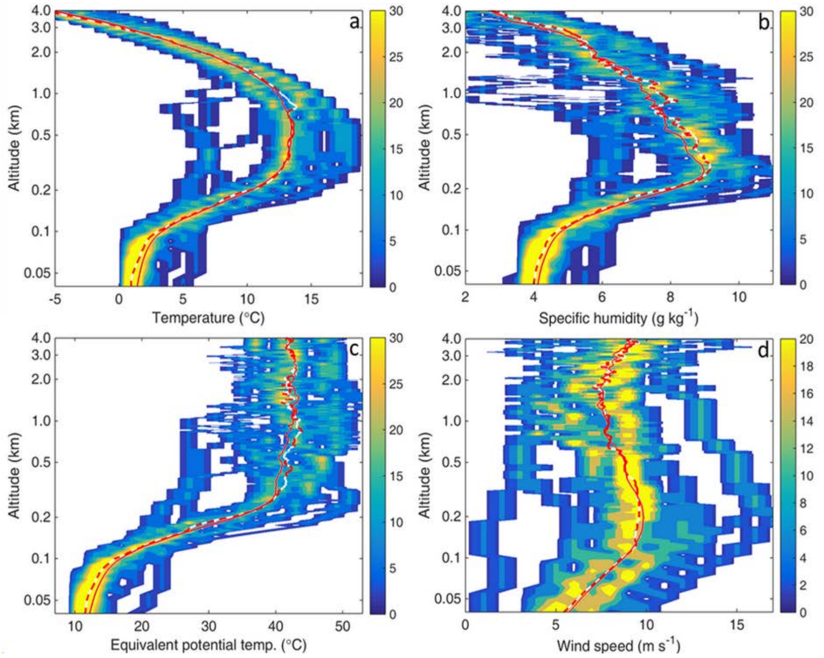


Figure 2.12 Composite vertical profiles from an epsiode with strong warm-air advection from land over melting sea ice (from Tjernström et al. 2015)

This is also an area of rapid transformation of air masses, either coming off the ice, where the sea-ice SEB has determined it characteristics, and out over substantially warmer water, or flowing onto the ice, where the sea-ice SEB transforms the warmer air from the open water. In summer, for example, sea ice is melting and the surface temperature is stuck at the melting point; warm and moist air from south has to adjust to these new conditions forming sharp transition zones (e.g. Tjernström et al. 2015). Figure 2.12 shows an example of a strong warm-air advection event over melting sea ice that occurred in the East-Asian Ocean during the ACSE research expedition, showing the very strong surface inversion that developed as warm continental air adjusted the melting-point surface temperature.

Similarly, in winter, cold air may exit the Arctic sea ice and flow out over considerably warmer water and rapidly transform; in such cold-air outbreaks so-called Polar Lows, intense hurricane-like cyclones, may form (Papritz and Spengler 2016; Terpstra et al. 2016). Both surface energy fluxes and clouds are important phenomena to consider in both cases.

2.2 TERRESTIAL

The disproportionately increased warming in the Arctic due to climate change will cause (and is causing) drastic changes in the terrestrial energy, carbon and water balances of the Arctic, with associated large effects on soil moisture, growing season, land cover (including species changes), greenhouse gas fluxes, albedo, snow cover, soil freeze-thaw periods and permafrost. Of crucial concern are the feedbacks between these land surface processes and climate warming; this is recognised as one of the greatest sources of uncertainty in climate prediction (IPCC 2007). There are also major consequences for human activities and populations in the Arctic.

The terrestrial component of the Arctic cannot be considered in isolation, but is strongly linked to the atmosphere and cryosphere and, through freshwater runoff and nutrient transport, to conditions in the Arctic Ocean (Figure 2-13). In addition, all the terrestrial processes are themselves inextricably linked. However, for practical purposes the terrestrial element of INTAROS will consider six fundamentally important components of Arctic land processes:

1. Spatial and temporal properties of snow
2. Spatial and temporal properties of vegetation
3. The Arctic greenhouse gas (GHG) balance (especially carbon dioxide and methane)
4. Permafrost and freeze-thaw cycles
5. Soil moisture and surface water
6. The freshwater balance of Arctic hydrological systems and the export of fresh water and nutrients into the Arctic Ocean.

The observing system needs to be able to measure these separate components in an integrated structure that allows their multiple interactions to be understood and quantified, both through empirical analysis and within suitable land surface models.

Although not specifically covered by these six components, an increasingly important aspect of the Arctic terrestrial system is human interaction with the environment and terrestrial ecosystems, for example because of oil and gas exploration and exploitation. These changes are driven by demographic, technological, economic and political changes, and are partly a response to changing conditions under climate warming. The observational data and modelling structure to be produced by INTAROS needs to be suitable for inclusion in integrated ecosystem management and anticipatory strategies for adaptation to socio-economic changes and the consequences of climate change.

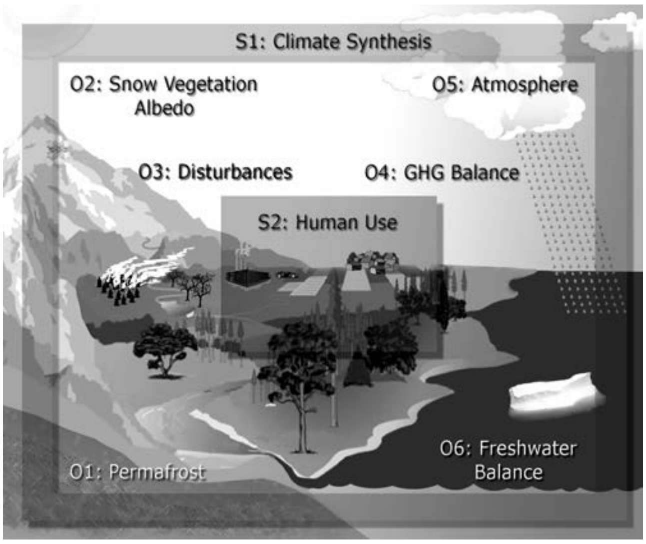


Figure 2-13 *This fig needs changing; it shows the different elements of the terrestrial component of the Arctic system, though needs to lose disturbances unless at some point we include the boreal forests & fire.*

Spatial and temporal properties of snow

Snow plays a major role in the climate, hydrological and ecological systems of the Arctic through its influence on the surface energy balance (e.g. albedo), water balance (e.g. water storage and release), thermal regimes (e.g. insulation), vegetation and trace gas fluxes, and feedbacks between snow and the climate system have global consequences (Callaghan et al., 2011a). Snow cover in the Northern hemisphere has been in decline over the last thirty years (Figure 2-14), and snow-free periods have increased in length (Callaghan et al., 2011b). Since the albedo of bare ground and vegetation is much lower than that of snow, this leads to increased absorption of solar radiation and hence warming, in a positive feedback process. The associated decrease in summer albedo is a substantial contributor to Arctic warming trends (Chapin et al, 2005). However, this is just one of the many processes in which snow plays a crucial role.

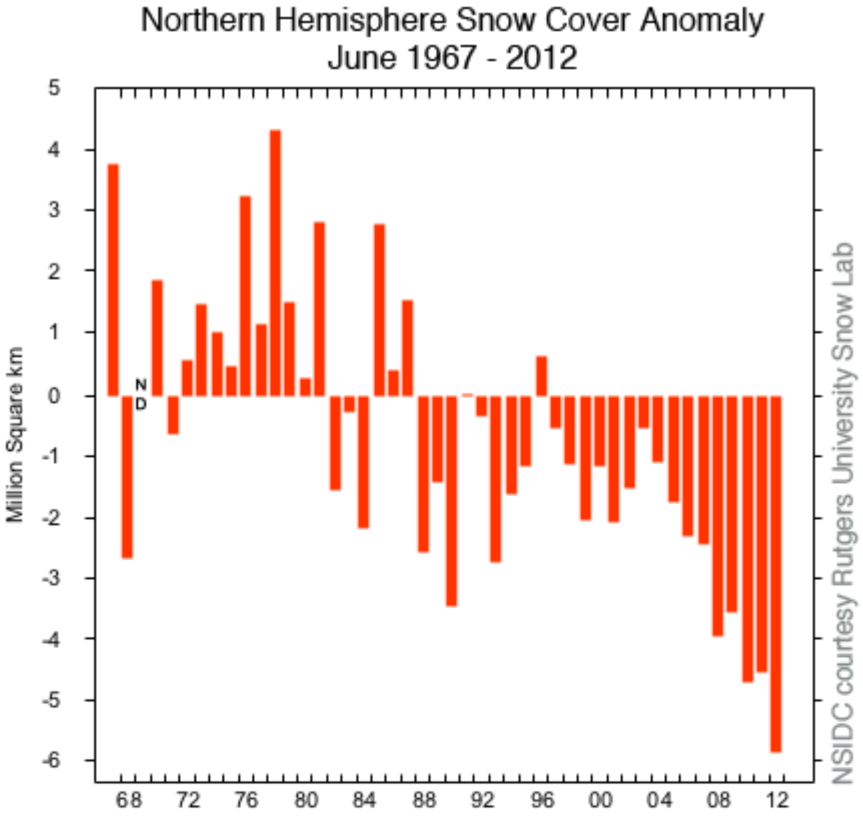


Figure 2-14 Snow cover anomalies (annual departures from the long-term mean) in the Northern Hemisphere show increasingly negative values since the mid-1990s. Source: http://nsidc.org/arcticseaicenews/2012/07/

While the extent and duration of snow cover is important for radiation balance, more important for hydrology is the amount of water held in the snowpack (the Snow Water Equivalent) and its variation over time. This provides a reservoir of fresh water that builds up over the winter and is released slowly during the spring and summer, with marked gradients as a function of latitude. Its dynamics are therefore important for plant functioning and for the timing and quantity of export of fresh water to the Arctic Ocean.

Snow cover has a further important role in modulating the transfer of heat between the soil and the atmosphere, since it is a very effective insulator, helping to keep the soil warm in autumn/winter and delaying the warming of soil in spring. This affects the conditions under which emissions of GHGs occur. Furthermore, this insulating effect is an important factor in permafrost dynamics.

In addition, snow interacts with vegetation in several ways. Depending on its depth, snow can prevent light reaching plants and hence the length of the growing season available to them. It provides a water source that for growth as long as it can permeate the soil when it melts, which is dependent on the freeze-thaw state of the soil column. Tall plants and shrubs can also affect snow by intercepting sunlight and delaying snowmelt.

Finally, the livelihoods and well-being of Arctic residents and many services for the wider population depend on snow conditions, so changes may have important societal consequences. Already, changing snow conditions, particularly reduced summer soil moisture, winter thaw events and rain-on-snow conditions have negatively affected commercial forestry, reindeer herding, some wild animal populations and vegetation.

Spatial and temporal properties of vegetation

Vegetation plays a major role in the energy balance and in the transfers of water, heat and trace gases between the surface and the atmosphere, and vegetation activity has exhibited major changes over the recent decades, as evidenced by the "greening of the Arctic" (Fig. 2-16). Because it has much lower albedo than snow, vegetation contributes to warming of the Arctic, with increased effects as low vegetation is replaced by shrubs that emerge from the snow cover. Vegetation is also important in the heat input to the soil from the atmosphere both by shading and, as in the case of Arctic mosses, providing an insulating layer between the atmosphere and the soil. The vegetation-soil system plays a major role in the hydrological cycle through evapotranspiration to the atmosphere; evapotranspiration and precipitation are usually the dominant terms in the water balance of the Arctic, although changes in soil moisture can also be important. Plants are fundamental in the carbon balance of the Arctic, taking up carbon through photosynthesis and providing sources to the atmosphere as they decay. It is therefore important to observe the spatial and temporal variation in vegetation, and to assess likely changes in the vegetation and its consequences for radiative effects, hydrological regimes and carbon balance. These observations need to be linked to global and regional numerical vegetation and hydrological models to provide biophysical fluxes (e.g., Net Primary Production [NPP], respiration, etc.).

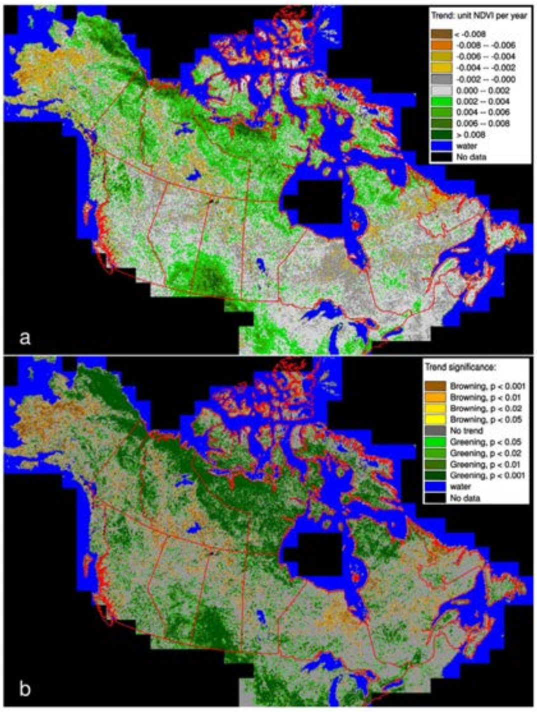


Figure 2-15 Greenness trend maps over the period 1984-2012 derived from Advanced Very High Resolution Radiometer (AVHRR) presented with a 500-m pixel size. (a) The greenness trend values, (b) The greenness trend significance levels (source: Ju and Masek, 2016).

The Arctic carbon balance

The Arctic and the adjacent boreal zone constitute key source and/or sink regions of the climatically relevant biogeochemical gases carbon dioxide, methane and nitrous oxide. Biological and chemical processes at the surface of the Earth primarily control these sources and sinks, predominantly land ecosystems. A large fraction of these areas is still relatively undisturbed by direct human impacts, although demands for resources (e.g. mining, oil and gas production), ecosystem products (e.g. wood at the southern limit of the Arctic) and recreational use are rising. These continental areas are also vulnerable to substantial climatic changes over the next decades as predicted by comprehensive simulations with climate models driven by past and anticipated future anthropogenic forcing factors. The extent to which greenhouse gas sources and sinks in the north region amplify or dampen the climate impact is at present difficult to quantify. Key feedback mechanisms are the compensating effects of an increased growing season versus increased respiration in a warming world, changes in wetland extent and emissions of methane, and melting of permafrost. However, recent observations have made clear that our understanding of greenhouse gas (GHG) fluxes in the Arctic is very limited. For example, it has been shown that emissions of methane can be unexpectedly high well into the cold season since decomposition activities can continue until heat loss from the soil shuts down their activity (Zona et al., 2016); this is linked to snow cover and its insulating effect that slows down the soil freezing process. It has also been shown that significant regions of Alaska have changed from being net sinks of carbon to net sources, with ensuing loss of their capacity to slow down climate warming (Oechel et al, 1993).

Permafrost and freeze-thaw cycles

Permafrost underlies more than 25% of the world's land area, mainly in the Arctic and boreal zones, but with some occurrences in mountainous and alpine regions. It is primarily controlled by climatic factors, but there are complicated interactions with snow, vegetation and disturbance. Climate change scenarios indicate that anthropogenic warming will be most pronounced at northern latitudes, which could cause the disappearance of up to 25% of the present terrestrial permafrost. Since more than 14% of the global terrestrial carbon is accumulated in the soils and sediments of Arctic permafrost environments, large increases of CH_4 and CO_2 emissions are therefore associated with degradation of permafrost, and represent a positive feedback to climate warming. In addition, because permafrost is highly sensitive to long-term warming, it is a valuable indicator for observing and forecasting environmental changes. Its degradation will have increasing impacts on infrastructure, greenhouse gas emissions, hydrology and ecology (Melvin et al., 2016). Freeze-thaw is a separate issue from permafrost, since the whole of the Arctic is subject to freezing of the upper layer of soil in winter, which may or may not be associated with an underlying permafrost layer. However, it has important effects because of its impact on plant activity and the availability of liquid water for plants.

Soil moisture and surface water

Soil moisture plays a fundamental role in the thermal properties of soil, water and heat fluxes to the atmosphere, plant growth and the emissions of GHGs, in particular whether carbon emissions occur as methane or carbon dioxide. It is strongly linked to vegetation cover and to the macro- and micro-topography of the Arctic (for example, grass tussocks in Arctic wetlands may be relatively dry while being surrounded by areas of standing water, yielding complex variation in conditions suitable for carbon dioxide or methane production). It is currently unknown whether Arctic soils will become wetter or drier, and how such changes will be distributed geographically, under Arctic warming and changes in precipitation patterns. There are associated changes in surface water, with seasonal ponds drying out due to enhanced evaporation, while new ponds are formed due to permafrost decay leading to slumping of the surface, both of which have effects on carbon emissions to the atmosphere.

The freshwater balance of Arctic hydrological systems and the export of fresh water and nutrients into the Arctic Ocean

The Arctic hydrological cycle involves complex links between land, ocean, cryosphere and atmosphere (Figure 2-16) that are currently poorly quantified. The hydrological cycle is inextricably connected to all biological and chemical processes occurring in the biosphere, atmosphere and cryosphere. Hydrologic interactions with terrestrial and aquatic ecosystems and their biogeochemistry control all life in the pan-Arctic region. Changing patterns of precipitation in the Arctic, combined with changes in the extent, duration and depth of snow cover will affect the fresh water inputs into Arctic hydrological systems, while changes in plant cover and the length of the periods of plant activity, together with changes in the thermal status of soils will alter fluxes of water to the atmosphere through evapotranspiration. When combined with possible changes in soil moisture, the net effect will be to alter the water available for freshwater runoff into the Arctic Ocean. In addition, human activities, such as building of dams in some northern basins, alter the timing and level of flow. Runoff to the Arctic Ocean also carries nutrients that are important for biological processes in the coastal ocean. The amounts of nutrients being transported and their changes under effects such as permafrost decay are very poorly quantified.

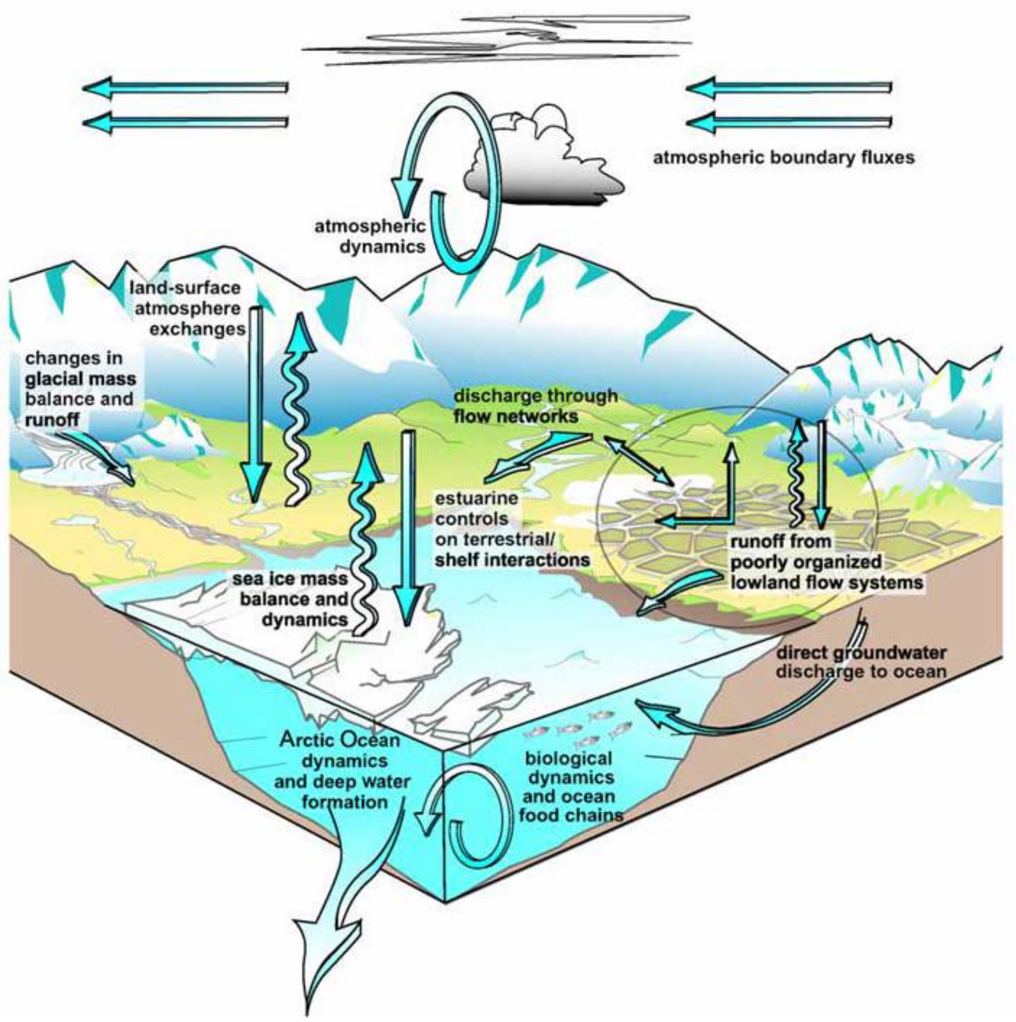


Figure 2-16 Schematic of the inter-linked processes involved in the Arctic hydrological cycle (source: Community-wide Hydrologic and Monitoring Program: Arctic CHAMP).

Terrestrial and freshwater ecosystems

The tterrestrial and freshwater ecosystems of the Arctic are home to a diverse array of plants and animals, including iconic species like reindeer/caribou, musk ox, geese, salmon and trout. These ecosystems constitute an irreplaceable cultural, aesthetic, scientific, ecological, economic and spiritual asset. Terrestrial habitats in the Arctic are bounded to the north by marine ecosystems. Therefore, northward ecosystem shifts caused by climate change are expected to reduce the overall geographic extent of terrestrial Arctic habitats – in particular for high Arctic habitats (Meltofte 2013). Arctic terrestrial ecosystems may disappear in many places, or only survive in alpine or island 'refugia'. Arctic freshwater ecosystems are undergoing rapid change in response to the influence of both environmental and anthropogenic stressors. The distribution and number of lakes, ponds, wetlands and riverine networks are being altered, with significant implications for the structure, function and diversity of associated biological communities. Key threats to these ecosystems include non-renewable resource development, contaminants, over-harvest, and invasive and human-introduced alien species, including pathogens and disease vectors (http://www.caff.is). There is an enormous deficit in our knowledge of species richness in many groups of organisms, and biological monitoring in terrestrial and freshwater ecosystems in the Arctic lags far behind that in other climatic zones. The multitude of changes in Arctic ecosystems, driven by climate and other anthropogenic stressors, will have profound effects on the living conditions of peoples in the region, including their cultures and the range of services that humans derive from such ecosystems (Arctic Council 2016). While ecosystem changes may provide new opportunities, they will also require considerable adaptation and adjustment.

2.3 CRYOSPHERE

The Greenland ice sheet and the other Arctic ice caps represent a key component in the hydrological budget of the Arctic, storing about a quarter of the world's freshwater outside Antarctica, equivalent to a global sea level rise of more than 7 metres. The Greenland ice sheet is intimately connected to the other parts of the Arctic climate system, responding to and causing changes in circulation of the atmosphere and the ocean. Atmospheric warming is increasing ice sheet surface melt leading to global sea level rise and causing changes in the ice sheet albedo affecting the global radiation budget. The increasing freshwater flux from the ice sheet is affecting sea ice formation, the local marine ecosystem and possibly the ocean circulation dynamics, while changes in the ocean currents reach the ice sheet outlet glaciers modulating the ice discharge and frontal melt. Understanding the interaction between the cryosphere and the other components of the climate system is required in order to increase our ability to project the impact of future emission scenarios on the ice sheet. Such an understanding in turn requires observations of key parameters and processes. In this report we make an initial attempt to identify the observational requirements and essential variables as well as the observational technology needed.

For the cryosphere, current and emerging research questions largely relate to the interaction with the atmosphere and the ocean in a changing climate. The unexpected and sudden acceleration of most of the Greenland ice sheet outlet glaciers in the mid-2000s increased ice discharge to the ocean dramatically over a few years exposing our limited understanding of the ice-ocean interaction and the impact of ocean currents on the overall dynamics of the ice sheet. After a decade of intensified research, much has been learned from process studies but the scarcity of observations limits our ability to apply this understanding to an ice-sheet-wide scale.

Large-scale changes in the atmospheric circulation increasingly impact the surface mass balance of the Greenland ice sheet and Arctic ice caps, dramatically increasing the surface runoff over the last decade. The increasingly persistent flow of warm air masses causes extreme melt events and larger overall meltwater formation on the ice sheet. This moves the equilibrium line altitude (where annual surface mass loss and gain balances) higher up on the ice sheet, with meltwater penetrating previously dry firn (old, compacted snow) causing firn warming and the formation of thick impenetrable ice layers routing the meltwater off the ice sheet limiting the refreezing. The physical characteristics of surface runoff from the Greenland ice sheet are thus changing, challenging our current ability to model future sea level rise from ice sheet mass loss.

The warming climate and the changing atmospheric circulation patterns are likely changing the accumulation on the Greenland ice sheet, and thus the overall mass budget. This also directly affects ice-marginal melt processes as the amount and character of winter snow has a significant impact on the surface melt the following summer. Indeed, melt has increasingly occurred out of season, deteriorating the snowpack and rain events has accelerated melt, where precipitation used to fall as snow with the opposite effect on surface melt. The interaction between precipitation and melt processes in the ablation zone and the lower accumulation zone of the Greenland ice sheet is thus important to understand the impact of atmospheric changes on the ice sheet runoff to the ocean.

Meltwater retention

Today, the percolation regime covers more than half of the ice sheet (Tedesco et al., 2011). In the record melt summer of 2012 (Box et al., 2012; Nghiem et al. 2012), melt water percolated into the uppermost elevations of the ice sheet. Validation of retention is a widely identified problem confounding the ability of ice sheet climate models to confidently predict surface mass balance (Ettema et al. 2009; Fettweis et al. 2013; Reijmer et al. 2012; Humphrey et al. 2012). Recent field data suggest a hysteresis in the permeability of firn: in a few consecutive extreme melt years, impermeable ice layers are formed and more consecutive average melt years are needed to re-establish a firn capable of completely absorbing melt water of single extreme melt years. This quantum process is illustrated in Figure 2-17 and examples from ice cores are given in Figure 2-18

Understanding the controlling factors of melt water percolation is fundamental to simulate melt water retention on the ice sheet. Recent field measurements indicate the build-up of impermeable ice layers in the near-surface firn, leading to an abrupt cut-off of porous firn at depth. Existing firn models are incapable of reproducing this mechanism due to a lack of implemented physics to describe percolation of melt water into previous years of firn. This “deep percolation”, a precursor to the formation of impermeable layers (Figure 2-18 a cores 1 and 4), is also lacking from current models.

Accumulation changes

Recent decades have been marked by a dramatic increase in Greenland ice sheet mass loss. However, far less attention has been placed on factors that put mass on the ice sheet - an increase in the mass input poses a negative feedback that has the potential to slow down mass loss. Net snow accumulation represents roughly 90% of the mass input to the ice sheet system (Box, 2013; Box et al. 2013). Greenland ice mass input is observed by ice cores (e.g. Bales et al. 2009), snow pits (e.g. Box et al. 2004), and snow stake ‘forests’ (e.g. Dibb and Fahnestock 2004).

The spatial distribution of net snow accumulation observations is sparse. There are 91 available cores that lack sub-annual resolution and are absent from areas where accumulation rates are highest. The time coverage of cores is variable with roughly an order of magnitude fewer cores representing years 1999-onward. Consequently, weather models are routinely used to represent the input side of the so-called ‘surface mass balance’ (e.g. Noël et al. 2015). However, the models can be up to 200% wrong in total precipitation, especially around the margins of the ice sheet where the mass input is largest (Lucas-Picher et al. 2012). Currently, operational regional climate models in Greenland are usually a hybrid between weather forecast model and general circulation model (e.g. Langen et al. 2015) that enforces the hydrostatic assumption (balance of gravity and upward pressure gradient, i.e. no vertical motion) and uses simple schemes of precipitation. In these state-of-the-art models, it is well known that complications will arise in particular when the fraction of precipitation falls as rain or the violation of the hydrostatic assumption in areas of complex and steep terrain, typical of coastal mountains where vertical motions are most definitely occurring in so called ‘gravity waves’.

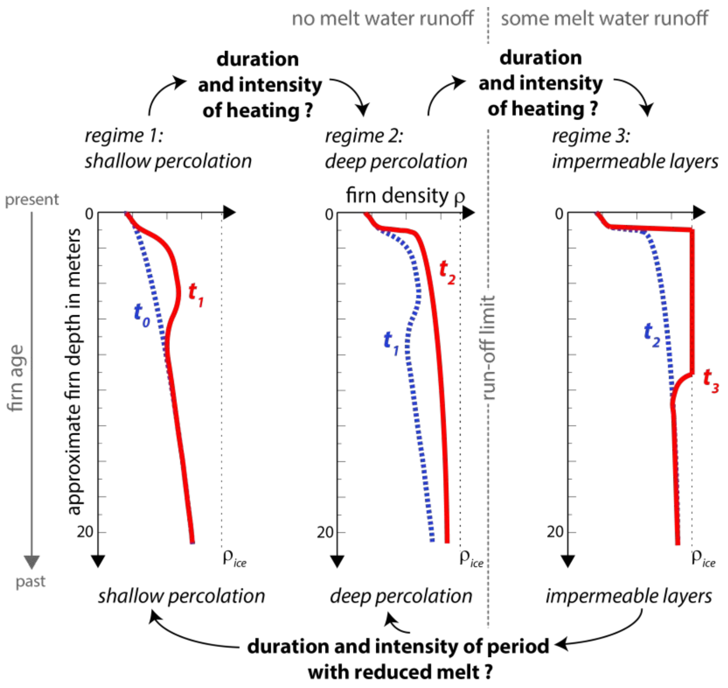


Figure 2-17 Hypothesized quantum transitions between three firn permeability regimes.

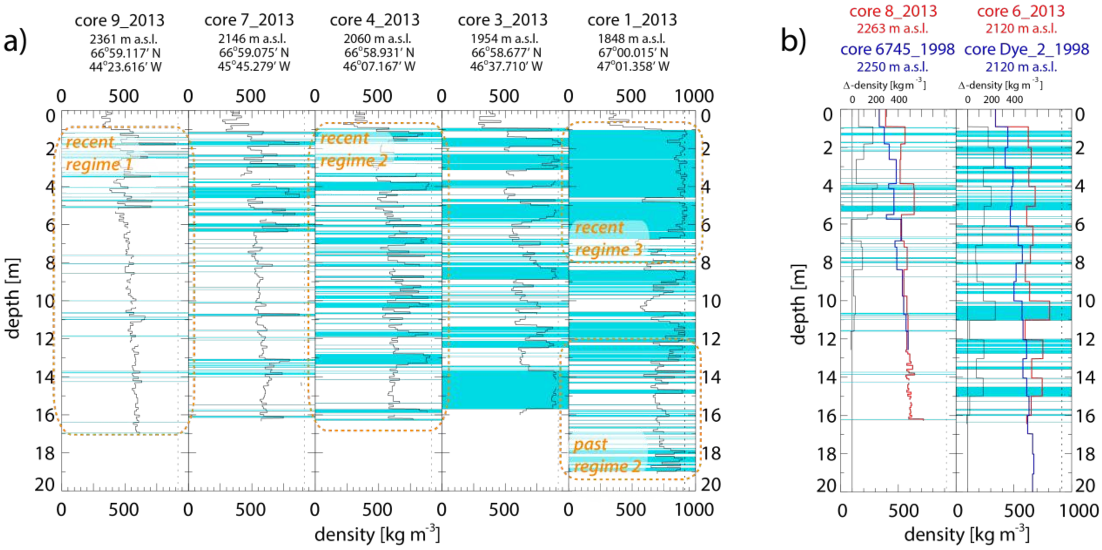


Figure 2-18 a) Selected cores drilled in 2013 representing the firn permeability regimes along the transect (ice lenses are in cyan, firn density in black). b) Selected core locations showing comparison of 1998 density profiles (blue) to 2013 (red), difference between the two curves (black) and ice lenses in 2013 (cyan). Source of 2013 data REFREEZE team members; 1998 data E. Mosley-Thompsen, pers. comm.

Regarding the absolute accuracy of Greenland mass input, little has been published. Burgess et al. (2010) warps weather model snow accumulation simulations through ice core points, uncovering 11% more mass input than previously thought. Yet, the highest extremes still remain unrepresented by observations because the cost of drilling is high relative to the recovered record length. A 50m core only produces under 20 years of data.

On the frontier is using ice cores to calibrate airborne radar mapping of snow layers to derive snowfall accumulation at high spatial resolution (Koenig et al. 2016). Yet, the ultra-high frequency airborne radar data needed is limited to just 2009-present. Another issue is mass input close to the long-term equilibrium line altitude (mass budget of zero), where the retrieval of firn core stratigraphy is disrupted by heavy surface melting. To get measurements in these areas relies heavily of year-to-year in-situ measurement, which is usually illustrated by conventional stake and snow pit density measurement.

Another component of Greenland ice mass gain is from net surface water vapour flux over the high ice sheet interior, amounting to 5-15% of the mass input (Box and Steffen, 2001). Warm years are associated with a whiter (brighter) upper elevation (Box et al. 2012), indicative of increased mass turnover (more surface frost) in warm years (Cullen et al. 2014). Yet, observations are limited to the atmospheric surface boundary layer (SBL). Hence, the issue of how much moisture is recycled within the SBL versus how much originates from the free atmosphere remains unresolved (Berkelhammer et al. 2016).

Ice-ocean interaction

The Greenland ice sheet increased its mass loss between 1992 and 2011, contributing to global sea level rise of c. 7.5 mm in this period (Shepherd et al. 2012). Roughly half of the increase in mass loss from the Greenland ice sheet between 1992 and 2011 was associated to the acceleration and retreat of outlet glaciers terminating in the fjords (Van den Broeke et al. 2009, Moon et al. 2012).

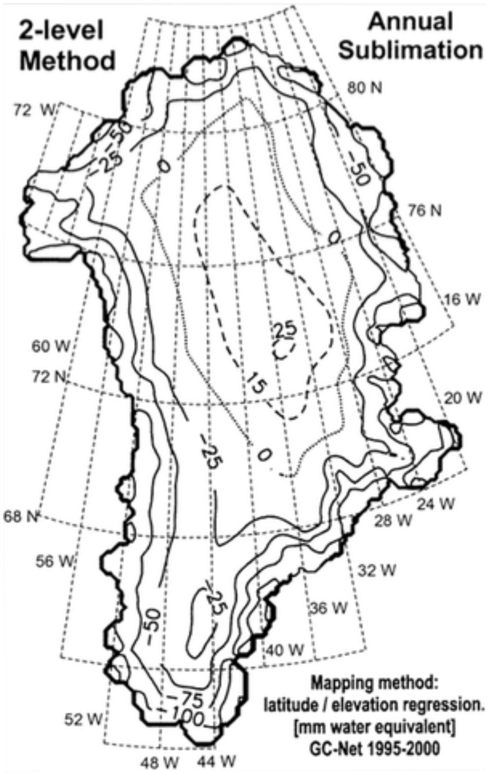


Figure 2-19 The only available observation-based estimate of ice sheet net surface water vapour flux (Box and Steffen 2001). Note the positive central values indicating mass input.

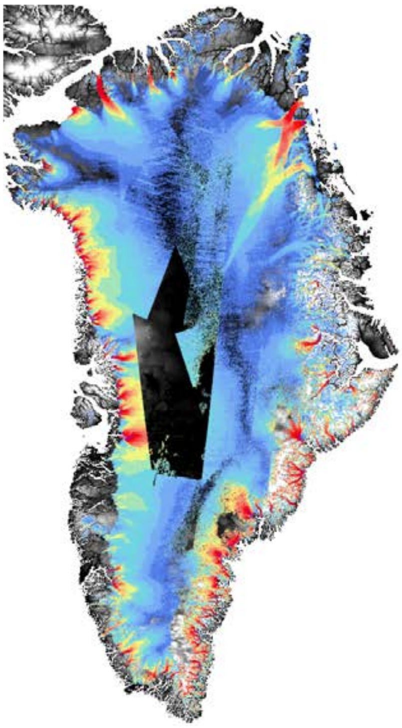


Figure 2-20 Greenland ice velocity map for winter 2016/2017 derived from ESA Sentinel-1 synthetic aperture radar data acquired between 1 November 2016 and 16 January 2017.

This sudden reaction of the Greenland ice sheet is still not well understood and has pointed out the shortcomings of current models of ice-dynamic behaviour. Finding the external forcing triggering this retreat and acceleration and characterizing the physical mechanisms responsible remains a challenging issue. Oceanic forcing has been pointed out as a plausible mechanism (Vieli and Nick 2011) highlighting the need to understand ice sheet-ocean interactions between the Greenland ice sheet and the fjords (Straneo et al. 2013, Joughin et al. 2012). However, changes in the surface meltwater formation on the ice sheet, also causes changes in the basal hydrological system affecting the ice dynamics. While process studies have increased our understanding of this connection over the last decade, observational in-situ data remain scattered or limited to a few locations. Getting the connection between ocean forcing, surface melt and ice dynamics right is essential in order to model the future overall response of the ice sheet to climate change and is an area of intensive research in need of consistent, long-term spatially distributed datasets of ice movement as the one illustrated in Figure 2-20

Freshwater flux

While the contribution of the Arctic land ice to global sea level rise is an important societal problem, the increasing importance of the Arctic region highlights the need to address local challenges. The Greenland ice sheet and local ice caps impacts a wide range of maritime activities such as shipping, cruise tourism, fisheries and offshore exploration through iceberg discharge, meltwater impact on sea ice formation and by altering the fjord circulation and open water polynya characteristics. Marine resource management is equally challenged by the rapidly changing physical conditions, requiring an increased focus on monitoring the critical input parameters, such as the combined freshwater flux from ice sheet runoff and iceberg discharge to ecosystem models at higher spatial and temporal resolution.

2.4 SEA ICE

Sea ice covers the polar oceans on both hemispheres and it has a large seasonal variability. Sea ice is an important component of the climate system because it has a high surface albedo compared to open water, together with the polar surface water it insulates the relatively warm ocean from the cold atmosphere, and it forms a barrier to the exchange of momentum and gases such as water vapor and CO_2 between the ocean and atmosphere. Regional climate changes affect the sea ice characteristics and those changes can feed back on the climate system, both regionally and globally. At the same time, sea ice affects the living conditions of the local population in various ways, as a platform for hunting and fishing for the sea ice related fauna habitat, and as a transportation ground in winter. On the other hand, sea ice hampers the ship traffic of goods to, from and through the Arctic.

Systematic, near real time (NRT) and long-term observations of the major sea ice variables is only possible using past and present satellite Earth Observation (EO) data. Sea ice charts are provided by the national ice services of the Arctic neighboring countries based on surface, and airborne, and on satellite observations of a large variety of sensors. At small scales, synthetic aperture synthesis (SAR) images are used, and on larger to hemispherical scales passive microwave sensors. While SAR observations like Sentinel-1 are able to meet this resolution requirement, they do not fulfill the requirement of daily covering the complete Arctic and full automatic analysis. The latter two requirements are met by passive microwave observations. These are available under all weather and daylight conditions, also during the polar night. Therefore, passive microwave observations are considered the backbone of global sea ice information. However, they are only available at coarser scales between 5 and 12 km, depending on the used satellite sensor and retrieval algorithm, with the higher resolving data products being obtained from observations at higher microwave frequencies (near 90 GHz) where the atmospheric influence is stronger.

Sea ice data from satellites has been collected for more than four decades and sea ice mapping is one of the most successful applications of EO data in climate change studies. Several sensors and retrieval methods have been developed and successfully utilized to measure sea ice area, concentration and drift [e.g. Breivik et al., 2009]. There are also other sea ice parameters of importance for climate research such as thickness, albedo, snow cover, temperature, duration of the melting season, the density of leads/polynyas and the volume of ridges. [e.g. GCOS, 2010; IGOS, 2007]. Remote sensing can contribute to retrieving quantitative measurements of most of these variables, even though GCOS defines sea ice in general as one ECV. In order to provide quantitative data on sea ice it is necessary to define the variables that can be measured. For climate change studies it is generally accepted that the most important and mature variables, where quantitative data have been obtained over several decades, are ice concentration, thickness, and drift.

There is evidence that the polar amplification of global climate change affects the sea ice covers of the Arctic and the Antarctic in different ways – in line with contrasting observations of climate relevant parameters during the last decades [e.g. Turner and Overland, 2009].

The reduction in Arctic ice thickness has been documented by combined observations from submarine sonar data, airborne surveys, in situ measurements and recently by satellite altimeter data from ICESat-1 and CryoSat-2 [e.g. Kwok and Rothrock, 2009, Laxon et al., 2013; Renner et al., 2014]. However, the thickness decrease estimates vary significantly depending on region, period of observation and methodology [e.g. Zygmuntovska et al., 2014]. The integrated estimate of ice thickness reduction reported by IPCC is 0.62 m per decade, corresponding to about -19.4 % per decade (Table 2-1). An important aspect for the Arctic is that the thickness reduction is closely linked to the decline of the multiyear ice cover [Comiso, 2012].

Snow on sea ice is a crucial parameter for climate-related processes. An important feature of snow is given by its high albedo. Therefore, snow on sea ice is a major factor for the Earth's energy budget. On the other hand, during summer, melted snow represents an important fresh water input, which affects density and salinity layers of the ocean. Besides its direct climatic impact, the snow layer also adds to the uncertainty of sea ice thickness estimates by satellite altimeters. Today operational sea ice monitoring and analysis is fully dependent on use of satellite data. However, new and improved satellite systems, such as multi-polarisation SAR, radar and laser altimeters, require further studies to develop more advanced sea ice remote sensing methods. In climate change studies based on satellite data, it is a major challenge to construct homogeneous time series from a series of consecutive satellite sensors needed for detection of changes over several decades [e.g. Meier et al. 2012]. At the same time there is progress in sensors and observation technology, which makes it possible to observe new parameters in the future.

It is important that the observational community works closely with the modeling community in order to communicate caveats and usefulness of satellite data products from the observational side and requirements to data and their importance from the modeling side. Available sea ice drift data are not necessarily free of inconsistencies due to changes in sensor technology used [e.g. Kern et al., 2014]. Available sea ice thickness data may be based on sub-optimal assumptions [Kurtz and Markus, 2012; Kwok and Maksym, 2014]. Nevertheless, these data are used by the modeling community [e.g. Holland et al., 2014] because these are the best we have at hand. Here phase 2 of the SICCI project will work on reducing the gap between the two communities and aims enhancing communication of uncertainties of observational data sets.

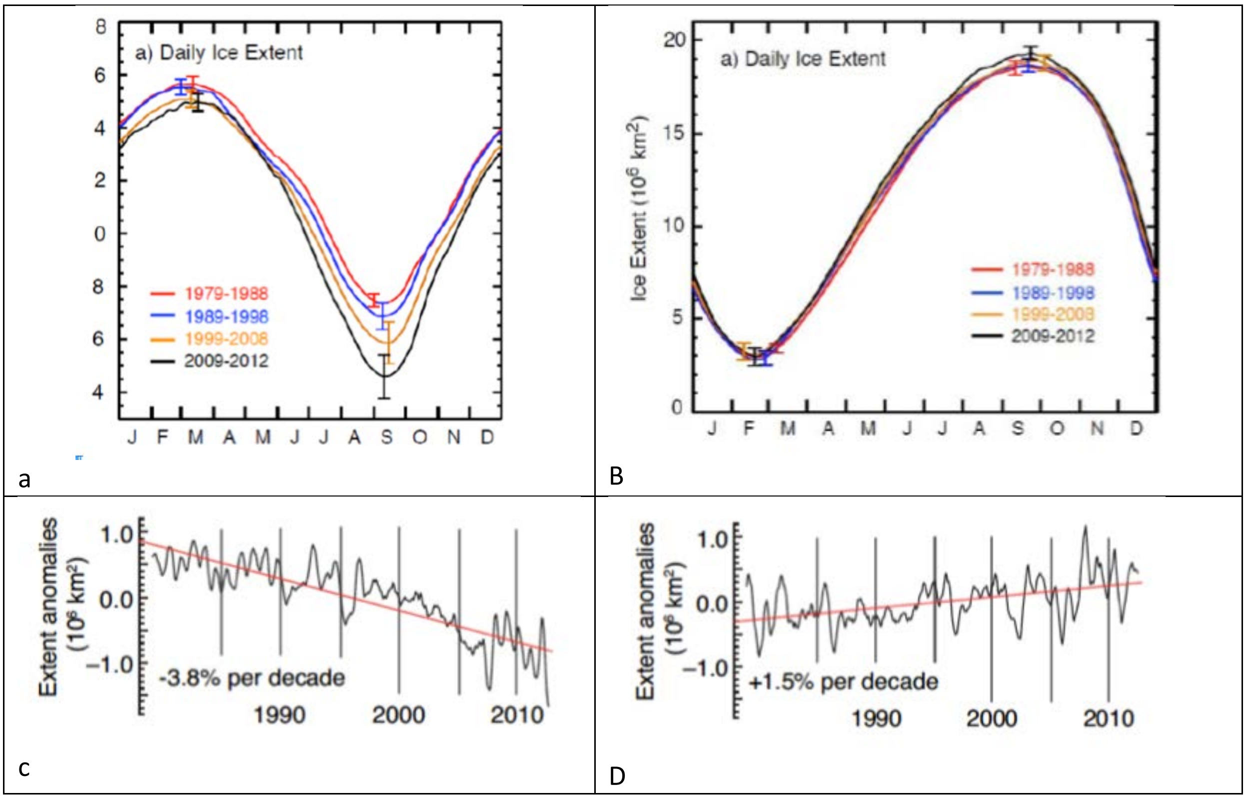


Figure 2-21 The seasonal cycle of sea ice extent for different periods in Arctic and Antarctic is shown in (a) and (b). Trend and anomaly of ice extent in Arctic and Antarctic is shown in (c) and (d)[Ref. IPCC 2013].

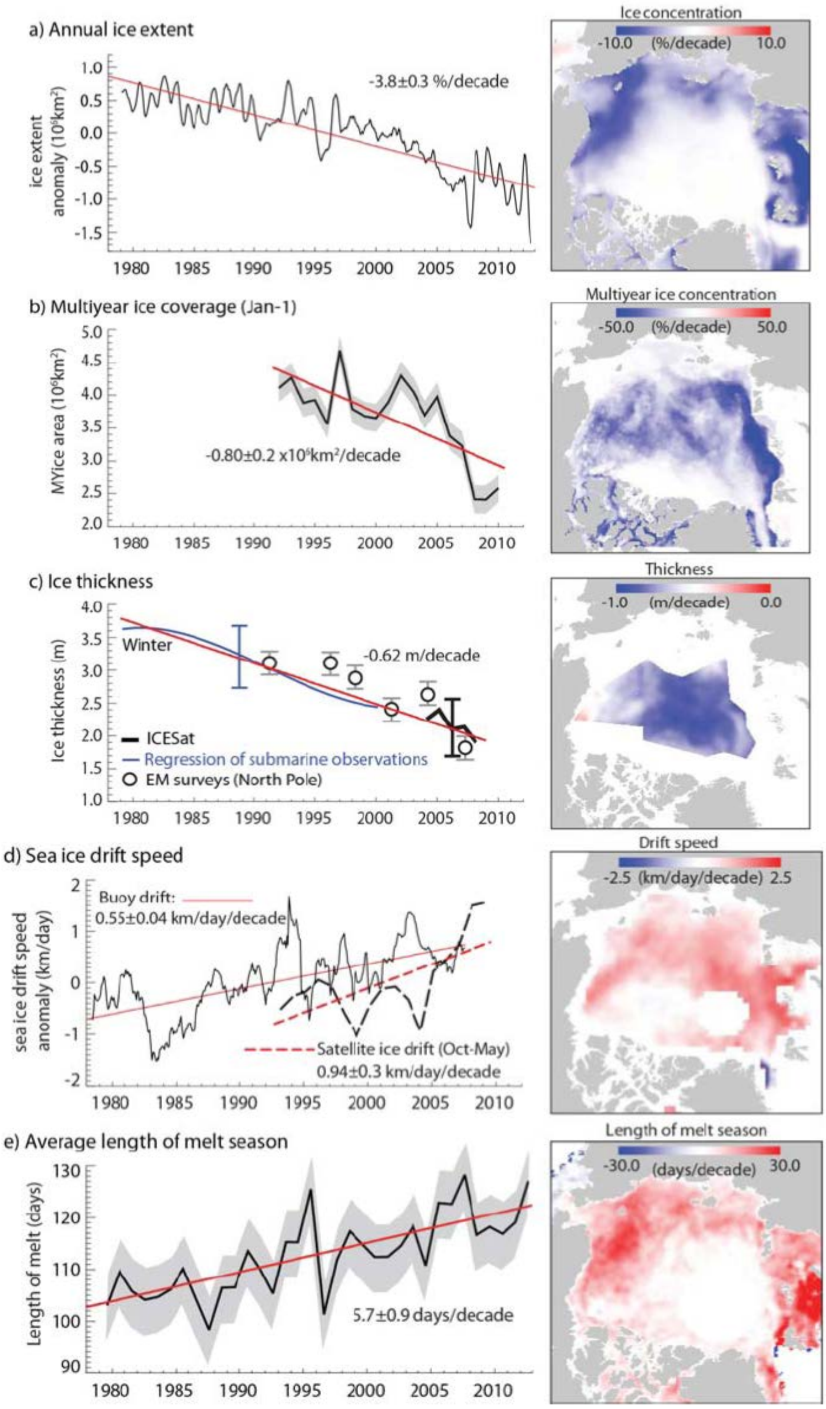


Figure 2-22 Summary of linear decadal trends (red lines) and pattern of changes in: (a) Anomalies in Arctic sea ice extent from satellite passive microwave observations [Comiso and Nishio, 2008, updated to include 2012]. Uncertainties are discussed in the text. (b) Multiyear sea ice coverage on January 1st from analysis of the QuikSCAT time series [Polyakov et al.,2012]; grey band shows uncertainty in the retrieval. (c) Sea ice thickness from submarine (blue), satellites (black) [Kwok and Rothrock, 2009], and in-situ/EM surveys (circles) [Haas et al., 2008]; trend in submarine ice thickness is from multiple regression of available observations within the data release area [Rothrock et al., 2008]. Error bars show uncertainties in observations. (d) Anomalies in buoy [Rampal et al., 2009] and satellite-derived sea ice drift speed [Spreen et al., 2011]. (e) Length of melt season (updated from [Markus et al., 2009]); grey band shows the basin-wide variability.

Global Change and Arctic Amplification

The most pronounced change in the Arctic sea ice over the last three decades is the reduction of the sea ice extent observed from time series of passive microwave data [Cavalieri and Parkinson, 2012], in particular the reduction of the summer ice, as shown in *Figure 2-25*. This change is also observed in reduction of multiyear ice fraction [Comiso, 2012], the increase of the length of melt season [Markus et al., 2009] and increasing ice drift [Rampal et al., 2009, Kwok et al., 2013], as well as in reduction of the ice thickness [e.g. Kwok and Rothrock, 2009], as shown in Figure 2-22, Rampal et al. [2011] describe how IPCC models miss Arctic sea ice acceleration (and thinning).

The reduction of the summer ice has dramatic impact on the climate, and is also influencing Arctic environment, ecosystem and fisheries and human activities such as ship traffic and offshore exploration [Johannessen et al., 2007].

Multiyear ice

While ice extent has decreased at a rate of -3.8 % per decade, the multiyear ice cover has decreased by -13.5 % per decade (Table 2-1). The multiyear ice extent is a very sensitive climate variable that is not yet established as an ECV. The amount of multiyear ice is important to quantify because multiyear ice is thicker, it has thicker layer of snow and has different physical properties compared to first-year ice.

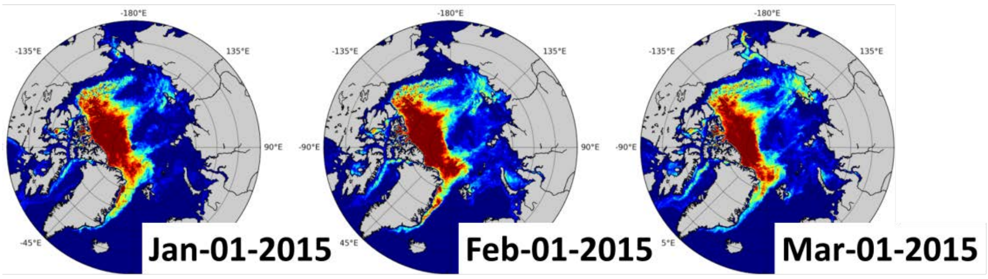
Methods to derive multiyear ice fraction exist but a thorough investigation and quantification of the uncertainties involved has not been undertaken yet. Algorithms combining radiometer and scatterometer data have the potential to improve current time series of the multiyear ice extent (Shokr and Agnew 2013). As the sea ice signature is not only determined by the sea ice type, but also by meteorological events like warm air intrusions, multiyear sea ice concentrations retrieved from satellite observations frequently need corrections based on the meteorological temperature and drift history (Ye et al., 2015, 2016). Figure 2-23 shows an example of the effect of the corrections.

Table 2-1 *Trends in Arctic sea ice.*

Parameter	Change per decade	Parameter	Change per decade
Ice extent: annual mean	-3.8±0.3 %	Ice thickness (1980-2000, submarine)	-16.5 %
Ice extent: winter	-2.3±0.5 %	Ice thickness (2004-2008, IceSat)	-22.7 % per 5 years
Ice extent: spring	-1.8±0.5 %	Ice thickness (Integrated)	-19.4 %
Ice extent: summer	-6.1±0.8 %	Ice drift (winter average)	+ 10.6 ± 0.9 %
Ice extent: autumn	-7.0±1.5 %	Length of melt season (total)	+ 5.7 days/decade
Ice extent: MY fraction	13.5±2.5 %	Length of melt season (margins)	+10 days/decade

A longer high-quality time series of the multiyear ice extent is also required for improved sea ice thickness retrieval because it permits an improved choice of sea ice densities [Laxon et al., 2013; Kern et al., 2014].

Before correction:



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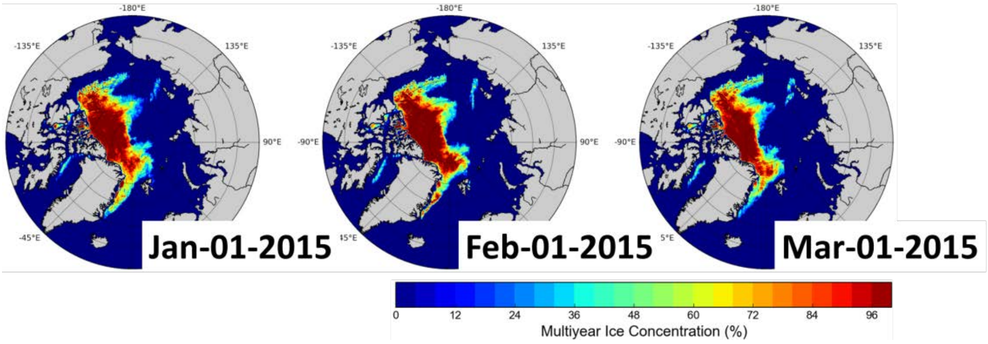


Figure 2-23 Examples of correction of multiyear sea ice concentration before and after correction for meteorological influences (Ye et al. 2016).

Sea Ice Thickness

Estimates of the sea ice thickness distribution in the Arctic Ocean are required for both operational and theoretical applications. Ship design and the construction of offshore platforms depend on the ice thickness for power and strength requirements. The thickness of the ice cover is a major factor controlling the rate of heat exchange between the ocean and the atmosphere which in turn plays a dominant role in local and hemispheric climatic studies (Bourke and Garrett 1987). Remote sensing of sea ice thickness is done for higher thickness with altimeters like CryoSAT-2 and daily for thin ice with L band radiometers like SMOS and SMAP (Huntemann et al. 2014, Kaleschke et al. 2012), see Figure 2-24 for an example.

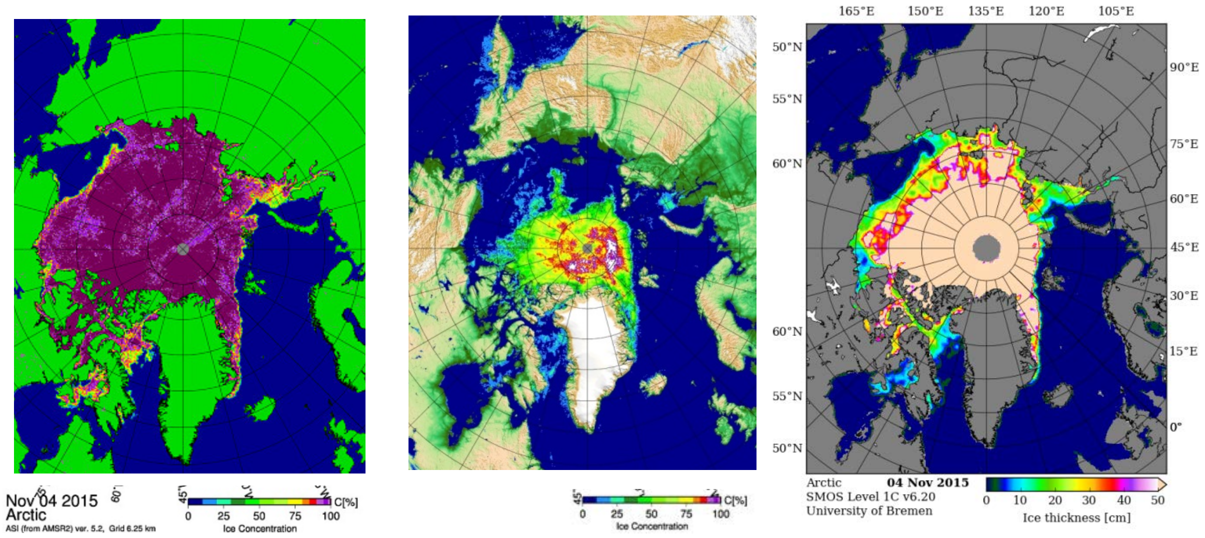


Figure 2-24 Left: Total sea ice concentration as retrieved by the ASI algorithm; middle: multiyear ice concentration; right: thickness of thin sea ice retrieved with SMOS; right: From https://seaice.uni-bremen.de.

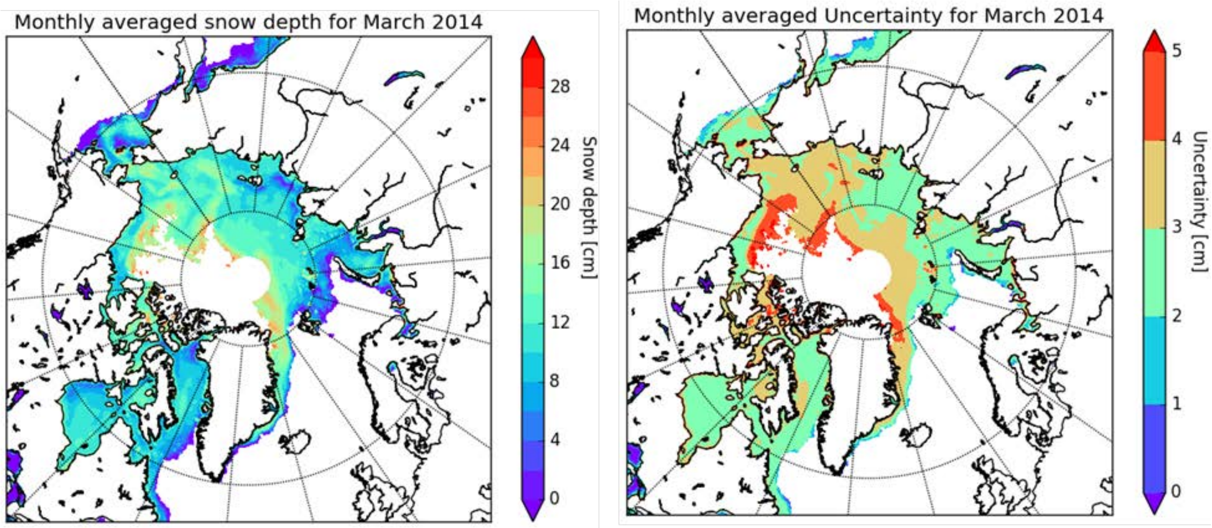
Snow on sea ice

The snow cover on Antarctic sea ice can be more layered than in the Arctic [e.g. Nicolaus et al., 2009] limiting the validity of current approaches to derive snow depth from satellite microwave radiometry [Markus and Cavalieri, 1998] and sea ice freeboard [Giles et al., 2008; Willatt et al., 2010]. In addition, a sea ice freeboard close to zero in combination with the quite dynamic environment further complicates snow depth retrieval and quality assessment [Maksym and Markus, 2008]. Remote sensing of snow on sea ice is a topic of current research. e. g. in the framework of the sea ice projects of ESA's Climate Change Initiative. It is mainly done with passive microwave satellite observations Figure 2-25).

In contrast to the Antarctic, where the suggested algorithms only use instantaneous observations, in the Arctic the retrieval yields higher uncertainties. Probably, also the sea ice type and other information about the meteorological history need to be taken into account. Figure 2-25 shows an example of snow depth, but with grid cells with multiyear ice concentration larger than 50% masked out.

Summer sea ice and melt ponds

Summer is the season when most the most dramatic changes of sea ice occur, but at the same time we know least about it at large scale where satellite observations are required. During the melting season in summer, the physical properties of sea ice change drastically. Among the most important consequences is the reduced albedo and increased energy input in the Arctic Ocean. Within the context of Arctic warming (Shindell and Faluvegi, 2009), the above mentioned seasonal alteration of the Arctic radiative balance has a negative long term effect on the sea ice cover and thus on global planetary albedo, which amplifies further warming (Pistone et al., 2014). The availability of temporally and spatially continuous sea ice albedo and melt pond fraction products is therefore crucial. These products can serve as input in GCMs or be utilized in self-consistent studies of melt evolution mechanisms.


Monthly averaged snow depth for March 2014

Monthly averaged Uncertainty for March 2014

Figure 2-25 Monthly average snow depth on sea ice (left) and variability (right) from an algorithm similar to Markus and Cavalieri (1998), but based on the gradient ration 6 and 19 GHz. In addition,

Melt ponds and sea ice differ by their reflective properties in the VIS and NIR range of spectrum, therefore both currently published melt pond fraction retrievals (Rösel et al., 2012, Zege et al., 2015, Istomina et al., 2015a,b) utilize optical radiometers (MODIS and MERIS). The retrieval by Rösel et al. is a neural network approach with predefined surface type classes; it uses MODIS 8 day composite surface reflectance product and provides corresponding 8 day composite of MPF. This temporal resolution might not be sufficient to resolve rapid melt onset and pond drainage events. The MPD retrieval uses level 1b MERIS TOA reflectances and gives swath-wise output, gridded to 12.5km polar stereographic grid to obtain daily averaged MPF. The MPD retrieval uses a physical model of sea ice and ponds to retrieve the MPF and sea ice albedo (Malinka et al., 2016). Currently, the whole MERIS dataset (2002-2011) is processed and available at Uni Bremen for climate model input or for specific ice morphology or melt pond studies (https://seaice.uni-bremen.de/melt-ponds/).

The MPD algorithm has been transferred to the OLCI sensor onboard Sentinel-3. As OLCI data are only available since October 2016, the first opportunity to apply the MPD retrieval to OLCI data in the Arctic would only be summer 2017; however, already now the sea ice albedo and melt pond fraction retrieval can be applied to OLCI data in Antarctica close to the Showa research station (Figure 2-26) where a surface melt event has been observed by a field party in the beginning of January 2017. Melt pond fraction retrieval from OLCI has been performed for 4 January 2017 and showed an increased fraction of melt ponds on the landfast ice.

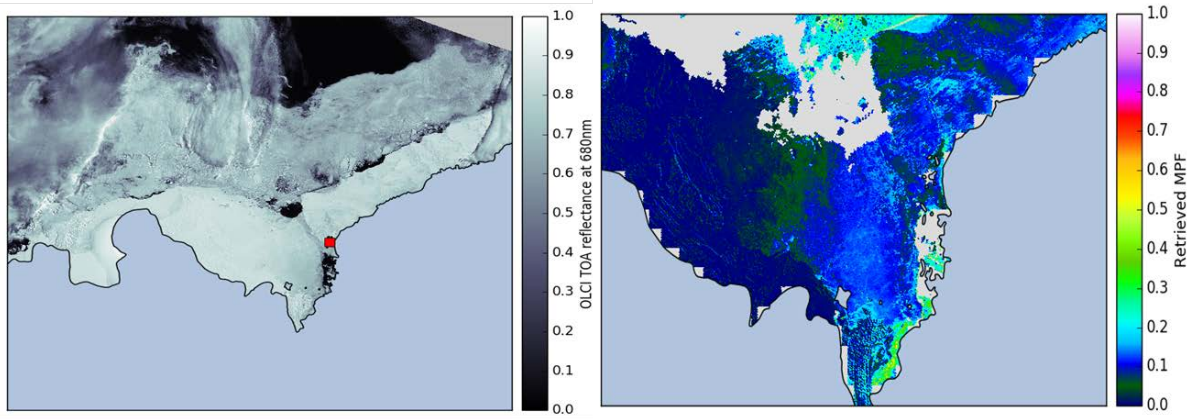


Figure 2-26 Left: OLCI top of atmosphere reflectance at 680 nm for the 4th of January 2017 in Antarctica, the Showa station (69°00'S, 39°35'E) is marked with a red square. Right: The retrieved meltpond fraction shows an increased melt at the landfast ice near the Showa station which agrees to the field observations (Istomina 2017, personal communication).

Sea ice leads

Leads are major sites of energy fluxes and brine releases at the air-ocean interface of sea-ice covered oceans. They are formed under the deforming forces of wind, wave and ocean current forces, and at the same time they are crucial to determine the stability of the sea ice against deformation. At mesoscales, lead fractions have been determined from SAR observations (e.g Zakhvatkina et al. 2017, Ivanova et al. 2016)), and at hemispherical scale from passive microwave observations (Bröhan and Kaleschke 2014).

2.5 OCEAN

2.5.1 Physics

The Arctic Ocean and the Nordic Seas are integral parts of the Atlantic meridional overturning circulation, and hence key regions for the global climate. Variation in sea ice and land ice coverage are of crucial importance because of their feedback on radiation (albedo), but also impact ecosystems in the Arctic domain. The melting of land ice leads to an increase in sea level and this increase in freshwater volume adds to the sea level rise through the thermosteric extension of the sea water under a warming climate. The main restriction to develop an effective arctic physical observation systems is the ice cover.

Ocean circulation and heat transport

The Norwegian Atlantic Current is the extension of the North Atlantic Current in the Nordic Seas and transports warm waters from the mid-latitudes to the Arctic Ocean. The Atlantic-derived water propagates in a boundary current through the entire Arctic Mediterranean. Along its pathway, Atlantic water transitions into several prominent branches, and releases heat to the surrounding water, ice cover and atmosphere.

Surface waters are densified through cooling and brine release during ice formation, and subsequently sink to depth. These sinking waters form a part of the dense overflow waters spilling over the Denmark Scotland Ridge, which closes the cyclonic circulation through the Arctic Mediterranean.

The main wind-driven ice and surface circulation features are the anti-cyclonic (freshwater storing) Beaufort Gyre, and the Transpolar Drift, which drives the freshwater towards Greenland and Fram Strait from where it is eventually exported to the subpolar North Atlantic.

Shallow shelf seas occupy approx. 40% of the Arctic Ocean's area. The shelves' current systems convey the freshwater from the sources at the rim to the central Arctic and the Transpolar Drift. In addition, upwelling mechanisms persist that transport the intermediate warm Atlantic-derived waters from along the continental slopes to the bottom waters of the shallow shelves, some of which contain submarine permafrost and gas hydrates. Offshore-directed winds in winter frequently open leads and polynyas in the ice cover, i.e. local "cold spots", characterized by strong oceanic heat loss and large sea ice formation rates. Polynyas produce those cold and dense shelf waters that spread beyond the shelf edge and ventilate the intermediate and deep layers of the Arctic Ocean, thereby forming the Arctic contribution to the dense waters of the Greenland-Shetland-Overflow.

Fronts and eddies

Fronts and eddies are interfaces between the geostrophically balanced flow and the so called sub-mesoscale flow, where non-linear terms become more important in the dynamical balances. In the Arctic, such features could preliminary be found in Fram Strait, where warm and saline Atlantic Waters enter the central Arctic Ocean in eastern parts of the strait, while cold and less saline waters leave the central Arctic in the East Greenland Current in western parts of the passage.

Freshwater cycles

The Arctic freshwater inventory has substantially increased over the last decades. This accumulation might be part of a multi-decadal oscillation, which is linked to the subpolar North Atlantic, where the freshwater can influence deep-water formation. The freshwater (solid and liquid) is eventually exported to the sub-polar North Atlantic. One part of the export occurs with the East Greenland Current, which episodically leaks freshwater into the interior Greenland and Icelandic seas, where it may impact deep water formation and hence the formation of overflow waters.

Riverine run-off

The upper Arctic Ocean receives freshwater from the Pacific inflow, through runoff from large rivers and through the distilling process of sea ice formation and melting. Nearly 11% of the global river run-off enters the Arctic, with the majority discharged to the Siberian shelves. This leads to a strongly stratified upper ocean, separating the warm and saline Atlantic waters from the sea ice and the atmosphere.

2.5.2 Biogeochemistry

The ocean is a key element in the global carbon and nitrogen cycles. Observed changes in the atmospheric concentrations of major greenhouse gases (e.g., CO_2, CH_4, N_2O) result from the dynamic balance between anthropogenic emissions and the perturbation of natural processes that leads to a partial removal of these gases from the atmosphere. There is a scientific need for global and long-term data to improve understanding of relevant chemical and biological processes, to assist in the design and interpretation of relevant chemical and biological processes, and thereby to improve predictive skills. Key questions include how the ocean carbon content and the biomass of the ocean is changing, what the rates and impacts of ocean acidification are, and how pollution impacts ocean productivity and water quality.

The advection of biogeochemical components into the Artic by the North Atlantic Current system is of great importance. This input of anthropogenic carbon into the Arctic ocean biogeochemical cycles is important to consider when generating a baseline for Artic ocean biogeochemistry and carbon system variables. To include advective contributions to the baseline components that stem from the thawing permafrost could with larger be accounted for.

The most important task will then be to calculate and measure how much anthropogenic carbon is imported to the Arctic by advection and how much GHG is released to the atmosphere through rivers and the ocean by remineralization processes of organic matter that stem from the Siberian permafrost.

To answer the first question, we suggest to develop a novel monitoring system consisting of a mooring array North of Svalbard in addition to make hydrographic and biogeochemical transect close to the array to produce a baseline and at the same time calibrate the autonomous sensors available for biogeochemical monitoring.

To answer the second question on how much transformed organic material that stem from the permafrost can be accounted for in the ocean requires similar mooring arrays strategically placed along the Russian shelf and slopes to capture these changes. These hotspots will be difficult if not close to impossible to reach.

The difference between the biogeochemical components already there, the advected will give the additional biogeochemical component added by thawing permafrost.

Organic matter cycling

Organic matter cycling refers to a group of processes, which either biologically transform or physically transport organic matter between the surface and interior ocean, or across the water-sediment interface. Biological transformations of organic matter include gains due to fixation of atmospheric CO_2 and inorganic nutrients into particulate organic matter, as well as losses due to grazing and respiration which transform particulate into dissolved organic matter, and organic carbon and nutrients back into their inorganic forms. Organic matter fixation is particularly important with respect to the biological component of anthropogenic carbon dioxide uptake, defined as the gross primary production by autotrophs minus the total respiration by phytoplankton, zooplankton, and the resident microbial community.

Acidification

Ocean acidification is a progressive increase in the acidity of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide (CO_2) from the atmosphere. It can also be caused or enhanced by other chemical additions or subtractions from the ocean. Acidification can be more severe in areas where human activities and impacts, such as acid rain and nutrient run-off, further decrease the pH. Ocean acidification is changing the seawater carbonate chemistry. The concentrations of dissolved CO_2, hydrogen ions, and bicarbonate ions are increasing, and the concentration of carbonate ions is decreasing. Changes in pH and carbonate chemistry force marine organisms to spend more energy regulating chemistry in their cells. For some organisms, this may leave less energy for other biological processes like growing, reproducing or responding to other stresses. Many shell-forming marine organisms are very sensitive to changes in pH and carbonate chemistry. Corals, bivalves, pteropods and certain phytoplankton species fall into this group. The biological impacts of ocean acidification will vary, because different groups of marine organisms have a wide range of sensitivities to changing seawater chemistry (Mostofa et al. 2016).

Pollution impacts

Marine pollution is a significant concern for ocean ecosystem health. Plastic debris in the ocean is now omnipresent. The durability is a common feature of most plastics, and it is this property, combined with an unwillingness or inability to manage end-of-life plastic effectively that has resulted in micro- and microplastics becoming a global problem. At the moment, our ability to detect floating plastics is limited to presence/absence data, but future sustained efforts to measure their concentrations, e.g., through under way automated data capture instruments, would help constrain the current very large level of uncertainty on their distribution.

Persistent bioaccumulating and toxic organic compounds are also ubiquitous in the marine environment, primarily because of human activity. Some are hydrophilic and others hydrophobic. Many of these compounds have chronic impacts on marine organisms especially at higher trophic levels amongst top predators. At higher latitudes, there are human populations, who are directly affected due to consumption of traditional foodstuffs.

2.5.3 Biodiversity and ecosystems

Arctic marine ecosystems provide a range of services and benefits of economic, societal and ecological value including the provision of food and the maintenance of habitat and species diversity. Like the case for physical ocean observations, the main restriction to developing good Arctic biological observation systems is the ice cover. In addition, in situ measuring is severely hampered by the prevailing harsh weather conditions and (especially ship-based observing) by distance from (major) ports. Consequently, even baseline information regarding biological conditions is generally lacking in the Arctic Ocean.

There are large knowledge gaps concerning the presence, abundance and distribution of planktonic organisms, fish species, birds, marine mammals and benthic organisms in the Arctic (CAFF 2013; Murphy et al. 2016). Furthermore, very little is known about the production capacity at species level, hence also in an ecosystem context. Since there is a severe lack of understanding of how the ecosystem functions today, predicting or even more vaguely anticipating its response to future changes in the Arctic Ocean's physical environment is challenging (Wassmann 2011; Wassmann et al. 2011).

Fortunately, the knowledge of the ecosystems of the more southerly parts of the Arctic, on the European side especially the Barents Sea, is at least the same level as for most temperate seas (Sakshaug et al. 2009; Jakobsen and Ozhikin 2011. Remotely sensed earth observations are regularly used for, e.g., detecting phytopankton blooms in the ice-free parts of the Barents Sea (Figure 2.27). Here there also has been coordinated (Soviet) Russian and Norwegian biological research surveys for decades, some time series go back more than 100 years. The surveys have traditionally targeted fish species of high commercial value (cod, herring, capelin), but over the last decade one has developed also far broader cruises targeting ecosystem understanding. An advanced observation, reporting and management system is used for the Barents Sea to support sustainable exploitation of marine resources.

Since the biology/ecology of distinct parts of the Arctic are influenced by very different regional and local drivers, an integrated Arctic system should provide biological data from all major regions. Some key areas have been identified. In Greenland that includes the North Water Polynya, Disko Bay, and the productive fishing banks on the south-western shelf. In terms of water mass transport, Fram Strait and the Barents Sea are the major gateways to the central Arctic Ocean and therefore, might be the main passages for the immigration/invasion of subarctic and boreal species with increasing water temperatures. For the Barents Sea it is important to expand some of the established measurement series in the Barents Sea further northwards, also beyond the shelf edge.

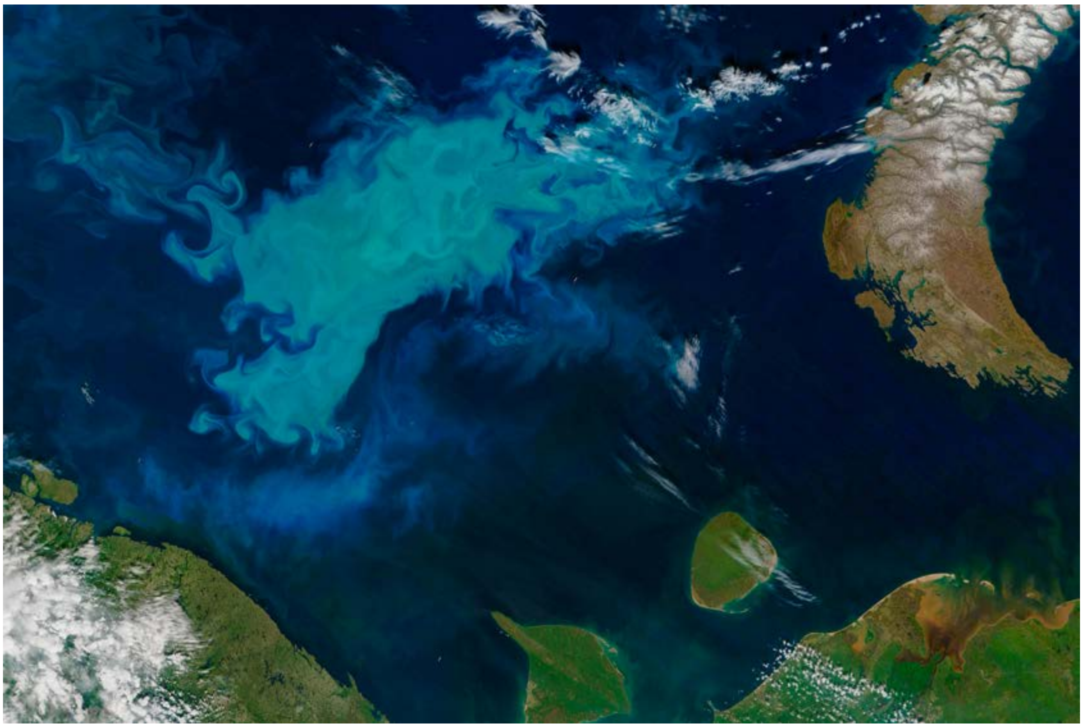


Figure 2-27 On July 6, 2016, the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite acquired this image of a phytoplankton (coccolithophore, turquise colour) bloom in the Barents Sea. Image courtesy of NASA: https://earthobservatory.nasa.gov/NaturalHazards//view.php?id=88316

3. REQUIREMENTS FOR OBSERVATIONS

3.1 ATMOSPHERE

The main problem in the Arctic, relevant to both observations and reanalysis products, for weather forecasting and climate monitoring, and for understanding and model development, is the lack of observations.

Atmospheric observations in the Arctic have many different uses and comes from different sources, making coordination or synthesis difficult.

Traditionally, global atmospheric observation networks have been built for the purpose of forecasting and the archetypical observations – often referred to as "operational" – are shared globally on the Global Telecommunications System (GTS). These observations provide information on the state of the atmosphere from which numerical modelling is initialized that provide information about the future state of the atmosphere on time scales from hours and days to months and seasons. Typically, deterministic forecasts are issued for 10 days or less, while ensemble forecasts, exploring the chaotic nature of the atmosphere, provide deviations from climatology on monthly to seasonal time scales. This information, in turn, feeds into other forecasting, for example for the development of the sea ice and for hydrological applications, such as river run-off, flooding, or the development of permafrost. In the recent several decades, the use of satellite irradiances has grown and is today an important component of the operational observation network, especially in the Arctic, where traditional observations are sparse.

Establishing optimal initial model conditions from observations is a process called "data assimilation". In this, a "first guess" is established from a short numerical model forecast; this result is then corrected by information from observations. This initial state forms the basis for a new short forecast, which is then corrected with new observations and so on in a continuous cycle. At given times, an initial state is selected for an independant longer integration; this is the forecast that will be provided to users. The initial state may also be perturbed to generate an ensemble of forecasts. Since the degrees of freedom of the system will always be many orders of magnitude larger than the possible number of ensemble members, perturbations are performed so that the most energetic developments.

Several assimilation techniques are in use. The most advanced is called Four-Dimensional Vibrational (4DVar) data assimilation; many models also use 3DVar. In both, corrections to the first guess from the forecast model is implemented using clever mathematics to provide information on likely errors from the model and errors and representatively of the observation. The difference between the two is that in 4DVar, time is considered; in 3DVar all observations within a time window are aggregated for the same model time. Another important difference is that since 4DVar is based on calculations of a so-called cost function, satellite data can be assimilated as radiances, which is what a satellite observes, using radiation modelling, rather than first calculating a vertical temperature profile through a retrieval algorithm, which is then assimilated as an observation.

More and more, with the increasing interest in Arctic climate, observation foci have become shifted to observe climate relevant variables and processes, and this can be achieved in two different ways: by actually observing things with remote sensing or in situ observations, or through reanalysis. Real observations in the Arctic are sparse, and hence the use reanalysis has become popular; sometimes reanalysis products are even referred to as "observations" which is strictly speaking wrong. A reanalysis follows the same process as for weather forecasting, using short forecasts and observations in an optimal blend. The important difference is that while in weather forecasting, modelling and data assimilation is continuously updated and improved, in reanalysis it is important that both model and assimilation techniques remain the same over time. Otherwise it becomes difficult to distinguish changes in the state of the (modelled) atmosphere due to changes in modelling or assimilation techniques from those actually happening, especially for subtler variables in the atmosphere. The strength of reanalysis is that the output is internally consistent and fully four dimensional; the weakness is that it is really a model product, with the uncertainty that comes from a model. The strength of using observations directly is that they are always "true" in a sense, to within the calibration of the instruments (or the retrieval software in the case of satellite data); the weakness is that also direct observations have errors that may be different for different sensors and that different observations are not constrained by each other. For example, the pressure gradient analysed from a network of surface pressure sensors is not always consistent with the wind observations from another network of observations, even if theoretically they should be.

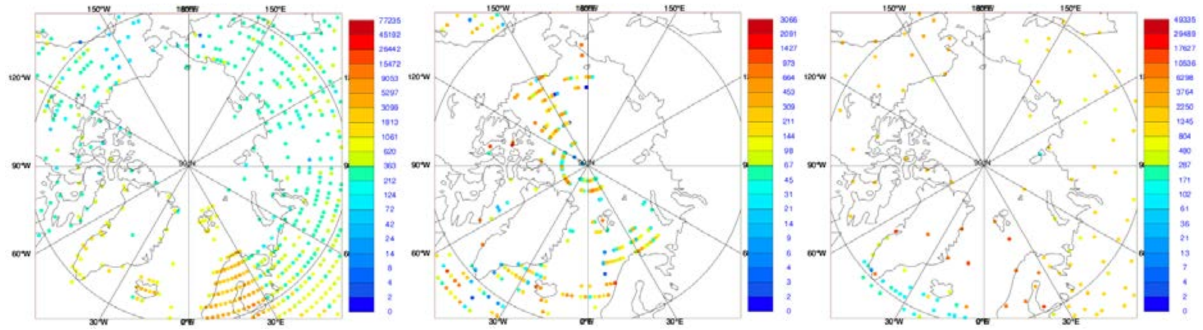


Figure 3-1Maps of observations used in data assimilation at the ECMWF during 2017-02-09- -03-11, showing (in color code) the number of surface pressure observations per grid box (left) from SYNOP stations and (middle) from drifting buoys, and (right) the number of vertical temperature soundings. Data available at http://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system#Availability

Observations may also be taken for the purpose of improving the understanding of the Arctic atmosphere and hence to improve models. All numerical modelling has a limited spatial resolution and there will always remain processes at smaller scales that will need parametric description. How this is performed depends heavily on the detailed understanding of processes that can only come from detailed research observations.

As an example of the lack of Arctic atmospheric observations, the left panel in Figure 3-1 shows the number of surface pressure observations that were used for data assimilation per grid-box area in the European Centre for Medium-range Weather Forecast (ECMWF) Integrated Forecast Model (IFS) from regular so-called SYNOP stations (commonly known as "weather stations") for a little over a month-long period in February/April of 2017. The middle panel similarly shows the number of pressure observations from drifting buoys. It is immediately clear that the number of surface-pressure observations, a cornerstone for weather forecasting, is very limited in the Arctic. There are no synop stations in the Arctic ocean simply because these need permanent non-moving platforms and, while the drifting stations provide less than a few hundred observations they are, first, limited to the western Arctic and, second, this number should be compared to e.g. central Europe, where the corresponding numbers are typically O(10^3-10^4).

Another backbone in data assimilation are the vertical soundings by free-flying balloons, carrying meteorological sensors, often called TEMP. During 1937 – 1971 the Soviet Union maintained drifting ice stations in the Arctic; after the collapse of the Soviet Union there was a break in this record. Russia restarted again in 2003 and new stations have been launched infrequently; the last one in 2015. The late winter 2017 situation is illustrated in the rightmost panel of Figure 3-2. Again, there are no sounding observations at all over the central Arctic Ocean. There are ~O(10^2) over the Arctic coastal areas; over Europe and the North Americas the corresponding number is at least one order of magnitude larger. In essence this means that we do not have any direct climatological information about the vertical structure of the central Arctic atmosphere from direct observations – at all.

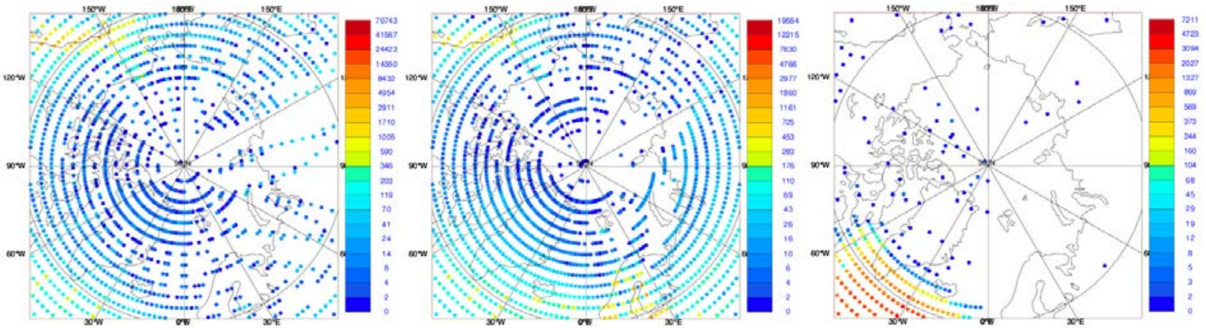


Figure 3-2 Same as Figure 3.1, but for temperature observations from aircraft at flight level, from (left) ACAR, (middle) AMDAR and (right) AIREP.

Upper atmosphere observations are also provided by aircraft observations through the automated ACAR and AMDAR systems (Figure 3-2 left two panels) but also here the numbers is comparatively low; O(10^1) in the Arctic compared to O(10^3) over continental USA and O(10^2) over the north Atlantic. Obviously this is connected to where commercial airlines fly their aircrafts; these observations are also limited to the flight levels of these aircraft. A few more observations come as AIREP; manual observations made by pilots and transmitted over radio.

Figure 3-3 ***Map and photos of the IASOA network of observatories (from Uttal et al.* 2016)**

To some extent, this relative lack of observations is balanced by satellite observations. The coverage of the central Arctic is good because all polar orbiting satellites passes over the Arctic twice per day. This provides excellent coverage from several satellites and these are now the main source of information for the Arctic Ocean for data assimilation into forecast models and reanalysis. Still, without baseline observations from e.g. radiosoundings, it is difficult to assess the quality of these products, that also often suffer from poor vertical resolution and problems in handling clouds.

In addition to operational observations there is also a network of so-called “super sites” around the rim of the Arctic Ocean. These are land-based stations, often on the coast, with extensive and continuous observations, often combining atmospheric observations with terrestrial observations. Especially worth mentioning here is the (International Arctic System for Observing the Atmosphere (IASOA; Uttal et al. 2016) network of stations (Figure 3-4). Although the instrumentation differs among the stations, and there are more stations in the western than in the Eastern Arctic, many of these stations do radiosoundings and some have advanced cloud observation instruments. IASOA was first established during the 4th IPY in 2007, but some of the stations, like those in Barrow, Alert/Eureka, Ny-Ålesund and Sodankylä existed also earlier; some of these time series are becoming long enough to start to fulfil climate needs.

In addition to operational observations and long-term observatories, research expeditions also contribute to the understanding of the Arctic atmosphere, and often provide additional operational observations that can be used to evaluate satellite retrievals and in numerical modelling experiments. Research expeditions are motivated by increasing process understanding and provides much more detailed information on various processes, for example on surface fluxes and clouds, but are limited in time. Figure 3-3 shows three examples. To the left is the track of the ground-breaking SHEBA expedition (Uttal et al. 2002) expedition when the Canadian coast guard icebreaker Des Groseilliers was frozen into and drifted with the sea ice north Alaska over a full annual cycle, 1997-1998. The middle panel shows tracks of the Canadian icebreaker Amundsen, in the Cape Bathurst flaw lead throughout the annual sea-ice cycle of 2007–2008, for the Circumpolar Flaw Lead (CFL) system study (Barber et al. 2010). Most expeditions, however, are concentrated to the summer season, when navigating in the central Arctic is easier; the rightmost panel shows three expeditions on the Swedish icebreaker Oden from the summers of 1996, 2001 and 2008 (Tjernström et al. 2012).

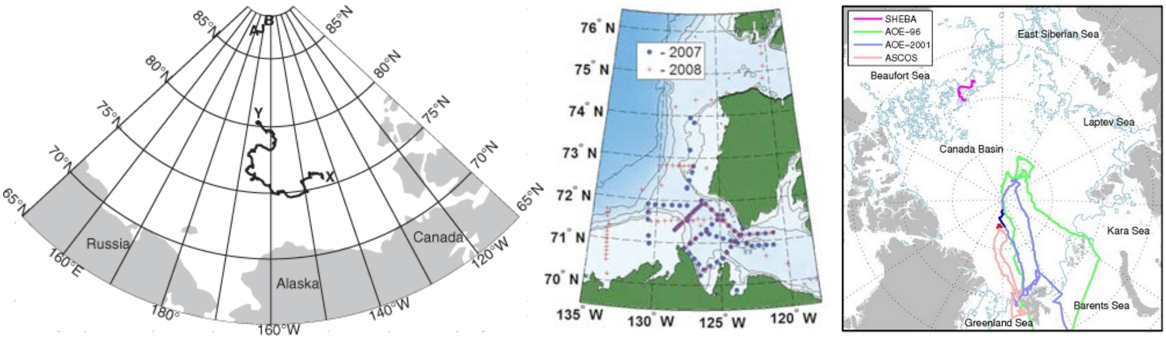


Figure 3-4 Examples of drift or cruise tracks for Arctic research expeditions showing (left) SHEBA, (middle) CFL and (right) three summer expeditions on the Swedish icebreaker Oden. See the text for a discussion.

While there is a strong summer bias from icebreaker expeditions, the two examples in Figure 3-3 from complete annual cycles, both were only single years.

In summary, there are large gaps in atmospheric Arctic observations, especially for the Arctic Ocean and in particular for the vertical structure of the atmosphere and also for important processes such as those related to clouds and the surface energy budget. This lack of data prohibits development of an understanding of the climate and weather in the Arctic and is this detrimental for both weather forecasting and climate projections in the Arctic.

The observational requirements are different for different depending on the applications: operational forecasting, climate monitoring, or process understanding and model development.

For weather prediction applications, the most important requirement is that the observations are in real time. To have any impact in data assimilation, the observations must be transmitted on the GTS within minutes of being taken. It is also important to have a sufficient frequency of observations with a reasonably s quality over time. This is because of the cycling of the short forecasts and the corrections from observation several times every day. The most critically lacking observation aspect for weather forecasting is information on the vertical structure of the troposphere – like that coming from radiosoundings. Second in importance is surface observations, of pressure, wind and temperature, such as today provided by some drifting buoys.

Many advanced data assimilation systems today have variational or other sophisticated methods for error handling and corrections, and hence the frequency and timeliness of observations is more relevant than absolute accuracy; it is also important to have a reasonable area coverage. Otherwise, one possible outcome in the data assimilation is that observations are simply rejected as erroneous, if the difference between the models first guess and the observations is too large, even if it might be the model that is off. With a single, or a few scattered, observation(s) combined with a model with systematic errors, observations may hence be erroneously ignored. Often rather basic information is required; assimilation systems usually do not consider things like clouds, turbulent fluxes, precipitation or visibility, but instead uses information on surface pressure, temperature, geopotential heights, moisture and winds throughout the atmosphere.

For climate monitoring, the absolute accuracy and location is more important than frequency of observations. High quality observations in long time series at specific locations are more important than a high frequency of observations. To be able to compute trends over longer time periods the data must have a consistently high quality and the data record must be long enough and be representative for a certain area. For an assessment of pan-Arctic climate development there also needs to be a sufficient number of observation locations across the region but they need not be as dense as for the forecasting application. Fewer stations with longer records is more important than many stations with short records. Maintaining the network over time is therefore of outmost importance.

For process understanding and model development representatively is important as well as degree of detail; observations must include parameters that tells something about the underlying processes for a specific phenomenon. Unlike, for example, for weather forecasting, observing the development of temperature and wind is not sufficient. Observations must also include observations of the components of the SEB to understand why temperature and wind vary as is observed. Similarly, to understand the clouds and the temperature, observations must also include information of properties of the cloud beyond cloud fraction and cloud-base height; one must also know amounts or cloud water, or at least the integrated cloud-water paths. To understand why and how clouds form, one must know the composition of the clouds and preferably also the size of the cloud particles and vertical velocities in clouds, as well as temperature and moisture profiles of the clouds. The more observations available of this type, the better we can constrain formulations in the models. Observations does not have to be representative for a large area as long as the area is representative for some phenomena or time period (e.g. season). Many different observations sites simultaneously are preferable but not necessary.

3.2 TERRESTIAL

Spatial and temporal properties of snow cover

Snow plays such a diverse and important role in controlling Arctic processes (e.g. in radiation and thermal balance, albedo, water balance, interaction with vegetation, access to grazing for animals, etc.) that monitoring its behaviour and properties is critical to understanding how the Arctic functions. Observing the seasonal spatial extent and duration of snow cover, combined with albedo, is of major importance for estimating the energy balance of the Arctic. Snow depth and density are also important because of their impacts on vegetation activity and thermal insulation of the soil, with related effects on permafrost active layer depth and dynamics. Together these two variables provide the snow water equivalent, which is a crucial element in the Arctic water balance, though snow water equivalent can also be inferred directly from microwave radiometry. All these quantities need to be observed at pan-Arctic scale, which implies the use of satellite data, but for calibration and validation it is essential to have in situ data together with regional scale estimates of snow depth and snow water equivalent from airborne lidar.

Spatial and temporal properties of vegetation

Because of its multiple functions in terms of the radiation, thermal, carbon and water balances, as well as its importance for animals and human beings, it is important to measure the changes occurring across the Arctic as a result of atmospheric warming, but also in more local regions where increasing human activity is changing vegetation communities (Kumpula et al., 2011; Yu et al., 2015). The primary requirement is for consistent spatio-temporal datasets of vegetation types and their associated processes. These include phenology, length of growing season, level of photosynthetic activity, albedo, Net Primary Production (NPP) and Net Ecosystem Exchange (NEE, which is a whole ecosystem process, so includes carbon fluxes from the soil). While some of these are available from satellites, others (such as NPP and NEE) rely either on in situ measurements or land surface models, possibly constrained by satellite quantities such as fraction of absorbed photosynthetically active radiation (fAPAR). In situ data are also crucial for validating inferences from satellite data.

The Arctic carbon balance

In order to gain accurate estimates of GHG emissions from the Arctic it is necessary to combine in situ, airborne and satellite measurements with atmospheric chemistry-transport models and ecosystem models. A primary requirement is to maintain and extend the existing flux tower network across the Arctic and add tall towers if possible. The most obvious gap is in Eurasia, where there are very few flux towers, but the locations of the flux tower sites in the current network of Alaskan, Canadian and N European needs to be reviewed to assess how representative they are of the whole Arctic region. Measurements need to be extended across the whole year since recent observations suggest that the cold season may be at least as important as the summer for emissions. Flux tower measurements need to be supplemented with in situ measurements of surface conditions (including weather, land cover and soil moisture) in order to support understanding of controls on the fluxes. The limited coverage by flux towers should be extended to regional scale using sensors carried on light aircraft. Attaining pan-Arctic measurements requires the use of column concentration observations from spaceborne platforms (currently GOSAT and OCO), which can be assimilated into atmospheric chemistry-transport models. A further requirement is a suite of ecosystem models or Dynamic Vegetation Models properly parameterised for Arctic conditions, linked to in situ data, in order to bring together bottom-up and top-down estimates of net emissions.

Permafrost and freeze-thaw cycles

The major requirement for permafrost observations is to extend and consolidate existing observing sites in order to understand the functioning of permafrost under present conditions and how permafrost might react under changing climate. This involves: (i) long-term field observations of active layer and permafrost thermal state, as well as carbon pools and decomposition processes, to detect climate signals in permafrost and its temporal and spatial variability; (ii) geocryological and paleoecological studies of permafrost sequences to reconstruct paleoclimate changes, and (iii) modeling the impact of climate change (IPCC scenarios) on permafrost, hydrology and vegetation and its feedback to the Earth System. The representativity of the current set of permafrost measurement sites needs to be assessed, and new sites added where there are significant gaps. However, because permafrost changes are typically slow (unless there are major disturbances, such as can happen when fires occur in forest growing on permafrost regions, of which there are large areas as in Eastern Siberia), then building up statistical evidence on trends requires long time series. Many of the current sites have insufficiently long high quality measurements to support such analysis. The whole of the Arctic suffers seasonal freeze-thaw cycles, so these are not a direct indication of permafrost. However, they are important because of their relation to the availability of liquid water and plant activity. In addition, changes in the period of unfrozen soil indicate a change the boundary conditions for permafrost formation and maintenance. Hence annual monitoring of the spatial and temporal patterns of freeze-thaw is needed, typically provided by satellite-borne microwave sensors.

Soil moisture and surface water

Long-term monitoring of the spatial and temporal patterns of soil moisture is crucial because of its role in plant productivity, the balance between methane and carbon dioxide emissions, and the hydrological cycle in the Arctic and freshwater runoff. Such measurements need to be linked to and if possible assimilated into basin-scale hydrological models that include weather data, land cover and topographic information in order to understand the balance between precipitation, evapotranspiration and water storage in Arctic basins. Such models need to include the storage of water by snow and its release over spring and summer, and their calculations can to some extent be validated by measurements of runoff. An important link is that between the freezing and thawing of soil, which control the availability of liquid water that can be exploited by plants for growth. A further related necessary observable is the seasonal occurrence of surface water as small lakes, not least because of their potential importance for GHG emissions.

The export of fresh water and nutrients into the Arctic Ocean

Particularly in Eurasia, river systems provide a major source of fresh water to the Arctic Ocean and in so doing carry nutrients, with important consequences for the biology of the coastal shelf. The size and variability of this runoff therefore needs to be measured for all major northward flowing rivers. Measurement of the volume of water input to the Arctic Ocean is primarily achieved by river gauges, and the maintenance of this system, together with adequate, timely reporting is a continual source of concern. Although nutrient runoff and its possible changes with permafrost decay are important, there are very few measurements of this variable and its constituents, but these are needed.

Terrestrial and freshwater ecosystems

Requirements for biological/ecological measurements in the terrestrial ecosystems have been described in the Arctic Terrestrial Biodiversity Monitoring Plan of the Circumpolar Biodiversity Monitoring Program (CBMP; https://www.caff.is/terrestrial/terrestrial-monitoring-plan) under CAFF (Conservation of Arctic Flora and Fauna; http://www.caff.is). Likewise, requirements for measurements in the freshwater ecosystems have been published in the Arctic Freshwater Biodiversity Monitoring Plan (https://www.caff.is/freshwater/freshwater-monitoring-plan). Further descriptions of gaps in knowledge are available in the Arctic Biodiversity Assessment (Meltofte 2013).

3.3 CRYOSPHERE

In the following, the identified requirements for monitoring of land ice in the Arctic have been divided between satellite remote sensing and in situ/near-surface observations.

Satellite remote sensing requirements

The requirements for the remote sensing part has recently been described in the User Requirement Document (URD) of the ESA Climate Change Initiative for Ice Sheets Phase 2 (Hvidberg et al. 2016) and is consequently summarized in the following:

Although ice sheet models are recently being developed to a higher-order that includes ice stream dynamics, the numerical schemes are complex. Model simulations require large computer resources and the capacity of the computing systems implies constraints on the possible space and time resolution. Large-scale ice sheet models are still running on a lower resolution than available satellite data, e.g. surface elevation and velocity, and are thus not using the full capacity of satellite based data in validations, but the gap has been closing in recent years. These models generally need long time series to understand the effect of large scale changes in climate and precipitation. To understand the processes controlling changes in ice flow and outlet glaciers, it is necessary to have access to high-resolution observations, and a number of studies have recently been devoted to studies of ice stream flow and seasonal behaviour of outlet glaciers using state-of-the-art higher-order models thereby increasing the demand for multi-year records of high-resolution observations in both time and space (Ahlstrøm et al. 2015).

The ice sheet modeling community is generally a diverse and scattered community working with various models of different complexity, different datasets, different resolutions, with focus on different goals. Ice flow modellers have been working independently with individually developed models, but in recent years, community ice flow models are being developed, and research groups are forming around these models. Several these models are being coupled to climate models, mostly off-line, but progress is made in fully coupled climate and ice sheet model systems. The purpose of these coupled modelling efforts has mainly been to investigate the evolution of the ice sheets in the past or into the future, to understand the contribution to the global sea level, and secondary to include feedbacks from ice sheets in coupled climate models. The international research community is relatively un-organized in regards of a formalized program to longterm monitor the Greenland Ice Sheet (GrIS) changes. Despite the immediate interest in GrIS mass changes, the reporting of such changes is mainly found in scientific publications, but a few systematic monitoring programs are formalized.

The addition of albedo data to the existing suite of variables would be very valuable to the climate model community. In a coupled climate model, all model components evolve freely, driven solely by the radiative forcing. In a coupled model setup, the ice sheet model is run solely by surface mass balance and temperature fields derived from the atmospheric part of the climate model (and possibly, an oceanic forcing based on ocean temperatures). The atmosphere and ocean components receive information on the ice extent and topography along with fresh water fluxes from the ice sheet model. When modelling the atmosphere, everything hinges on radiative balances at the top of the atmosphere and at the surface. Consequently, the surface albedo is crucial to the model. In most climate models, the current albedo parameterizations over ice and snow surfaces are rudimentary, and major efforts are put into improving these albedo parameterizations. Consequently, albedo products are indispensable asset in coming and ongoing projects on development of albedo parameterizations in climate models.

In situ/near surface observation requirements

The observations made on land ice in the Arctic are scarce and rarely sustained as long-term monitoring programmes. Yet, these observations are crucial both as validation/calibration data for satellite data products and also as observations that cannot be obtained from satellites.

As glaciological monitoring programmes are few and relatively recently established, no formal documents define practices or set specific requirements for all observed parameters as is common in more mature fields, like meteorology and oceanography. Often, parameters are to be used in other scientific fields and requirements are defined in this way. This transition is not without problems, as when established WMO requirements for weather stations on land are applied to stations situated on a melting, moving ice sheet surface. The inclusion of data from glaciological monitoring systems sometimes requires flexibility in inherently rigid data ingestion systems for e.g. weather forecasting.

A basic requirement for validation/calibration of satellite-derived essential climate variables (ECV's) is that observations of the desired parameters are conducted with higher fidelity and higher spatial and/or temporal resolution.

3.4 SEA ICE

For operational sea ice charts and numerical sea ice predictions, the time constraints are less strict than for atmospheric data because sea ice develops at a slower scale. Ice charts are updated between daily and weekly. As a consequence, observations are required in near real time (NRT) that is within hours. Data from many different sources enter the sea ice charts, with satellite observations at a main source. As ships are objects of the scale of 100m, operational sea ice information is desirable at a similar scale. SAR images have sufficient resolution, but their automatic analysis is still subject of research (Zakhvatkina et al. 2017). Therefore, preparation of ice charts still includes a percentage of human interaction. While the total sea ice concentration can be retrieved from passive microwave satellite observations quite reliably, the influence of weather (atmospheric water vapor, cloud liquid water and precipitation) on the retrieved ice concentration near the sea ice edge is still to be improved.

Critically lacking observations are reliable sea ice concentrations in summer, when the sea ice is wet and covered with melt pond so that the sea ice signatures of both optical and microwave sensors are changing and the sea ice concentration cannot be retrieved at the required accuracy.

For operational ice navigation of ice going ships, also thickness of sea ice up 1 m is required, and the amount of snow on top of the sea ice, which increases the ship friction at a similar amount as an equally thick ice layer would do.

For sea ice related climate data products based on satellite observations, the same requirements hold and climate data products based on them frequently have global or hemispherical coverage. While at low ice concentrations, driven by ship operation requirements, an accuracy of 5% to 10% is sufficient, at high accuracy the requirements are driven by the heat transfer from the ocean to the atmosphere: leads represent 1 to ~2% of the sea ice area in winter, but account for ~70% of the flux of heat and water vapour (Fichefet and Morales Maqueda, 1995). However, above 95% sea ice concentration, modulations of the microwave signal are mainly controlled by variations of the sea ice emissivity so that the goal of ice concentration accuracy below 2% at high ice concentrations may be difficult to achieve from passive microwave observations alone.

As the heat content stored in the sea ice is proportional to its volume, in addition to the sea ice concentration also the sea ice thickness is needed, which in turn requires the snow depth on sea ice if the thickness is determined from altimeter measurements like CryoSAT-2.

Sea ice concentration data belong to the longest time series (since 1972) available from satellite observations. Of course, they have been collected by a long series of satellite sensors of varying quality (mainly increasing over time) in terms of number of channels and horizontal and radiometric accuracy. It is essential to make these combined data sets consistent over time and especially from one sensor to another in order to avoid artificial trends.

3.5 OCEAN

A preliminary approach to define user requirements, as well as to determine the appropriateness of the available ocean data, has been initiated in the framework of the Copernicus Marine

Environmental Monitoring Service (CMEMS), in the European Marine Observation and Data Network (EMODnet), and in the Framework for Ocean Observing (FOO) of real-time services utilized by the Global Ocean Observing System (GOOS).

The Copernicus Marine Environment Monitoring Service (CMEMS) provides regular and systematic reference information on the physical state, variability and dynamics of the ocean and marine ecosystems for the global ocean. The observations and forecasts produced by the service support all marine applications, e.g., the provision of data on currents, winds and sea ice help to improve ship routing services, offshore operations or search and rescue operations, thereby contributing to marine safety. The service also contributes to the protection and the sustainable management of living marine resources for aquaculture, fishery research or regional fishery organisations. CMEMS provides information to four areas of benefits, i.e., Maritime Safety, Coastal and Marine Environment, Marine Resources, and Weather Forecasting. Each of these four areas comprise at-sea activities that require operational marine services.

The European Marine Observation and Data Network (EMODnet) is a long term marine data initiative from the European Commission Directorate-General for Maritime Affairs and Fisheries (DG MARE) underpinning its Marine Knowledge 2020 strategy. EMODnet is a consortium of organisations assembling European marine data, data products and metadata from diverse sources in a uniform way. The main purpose of EMODnet is to unlock fragmented and hidden marine data resources and to make these available to individuals and organisations (public and private), and to facilitate investment in sustainable coastal and offshore activities through improved access to quality-assured, standardised and harmonised marine data which are interoperable and free of restrictions on use. The EMODnet data infrastructure is developed through a stepwise approach in three major phases. Currently EMODnet has finished the 2nd phase of development with seven sub-portals in operation that provide access to marine data from the following themes: bathymetry, geology, physics, chemistry, biology, seabed habitats and human activities. EMODnet development is a dynamic process so new data, products and functionality are added regularly while portals are continuously improved to make the service more fit for purpose and user friendly with the help of users and stakeholders.

The Framework for Ocean Observing (FOO) provides a system-level view of effective practices for setting requirements (e.g., common language, consistent handling), coordinating observation networks, and delivering sustained information products. The Framework is organized around Essential Ocean Variables (EOVs), rather than any specific observing system, platform, program, or region. Through broad community collaboration, the Framework helps to improve communications and data sharing, resulting in faster and better-coordinated information to support research and societal needs.

High-level objectives of the Framework include to take advantage of existing infrastructure and lessons learned from other observing efforts, to deliver an observing system that can, and will, adjust to meet user requirements, to develop coordinated and interoperable data management streams, to help the ocean observing community to sustain and expand its capabilities, and to promote the alignment of independent groups, communities, and networks.

For the biogeochemical components and the carbon system variables regular sections, flow and go system in combination with autonomous sensors on different platforms as moorings will be the most promising approach. It is also important that on repeat sections also different tracers as SF6 and CFC's are measured to obtain age control on different water masses in the Artic. A good overview of the age structure of water masses inhabiting the Arctic ocean will allow us to strategically select the younger water masses most likely to be affected by hot spot changes.

Requirements for common biological/ecological measurements are described in numerous publications by the ICES community (International Council for the Exploration of the Sea; www.ices.dk). For biodiversity, monitoring requirements and status there exists many reports under the Arctic Council's CAFF (Conservation of Arctic Flora and Fauna; http://www.caff.is) umbrella.

4. ESSENTIAL VARIABLES TO OBSERVE

4.1 ATMOSPHERE

What variables that are essential to observe is again a function of purpose. For weather forecasting and data assimilation, including reanalysis, the list essential observed variables are limited to those variables that can successfully be included in the real-time data assimilation. These include atmospheric pressure, temperature and moisture, and wind speed and direction, at the surface and vertically through the atmosphere. This can come from direct observations or from satellite observations via a retrieval process; in some assimilation systems, satellite data is assimilated directly as radiances.

Forecast models, on the other hand, produces many in principle observable variables, that needs to be evaluated against observations; model verification This of course includes the observations that was used in the data assimilation but also variables like clouds, precipitation and visibility as well as variability of all these variables. For simple verification purposes, variables do not have to be extremely sophisticated. Observations for the purpose of model development is different. Then, for example, the amount of clouds (cloud cover) or even the geometry of clouds (cloud bases and tops) is not sufficient. One also needs to observe cloud-water phase and amounts, droplet/crystal size distribution and possibly also aerosols concentrations. Other more sophisticated observations that are necessary for model development are direct observations of radiation turbulent fluxes at the surface and the radiation fluxes at the top of the atmosphere.

For climate purposes, observations are usually not blended with the modelling itself; observations are used to improve and test models, but have no place in the running of a fully coupled climate model. There is a grey zone, for example, in what is called decadal forecasting; this is arguably both forecasting and climate modelling and the results are sensitive to initial conditions, especially in the ocean. For developing climate models, the observation requirements are essentially the same as for weather forecast models, with some additions of variables that are climate relevant but not of primary importance in weather forecasting. This could be additional trace gas and aerosol observations, and surface fluxes of trace gases.

It is very hard to see that sustained pan-Arctic Ocean climate monitoring could be done any other way than by satellite. At the same time, satellite observations today are not mature enough to replaces radio soundings; accuracy and vertical resolution is simply not adequate and therefore a challenge for science is to make satellite observations more useful.

4.2 TERRESTIAL

With the exception of in situ measurements of GHG emissions, all variables of interest to the terrestrial domain of INTAROS are considered Essential Climate Variables as defined by the Global Climate Observing System (GCOS 2015). However, in many cases there are paricular issues to do with these quantities that specific to the Arctic, as noted below. The section on GHG variables is specific to the Arctic.

Spatial and temporal properties of snow

Snow covered area, snow depth, snow density, grain size and snow water equivalent are a set of inter-related variables that give the gross properties of snow cover at a given time. These need to be observed on a regular basis throughout the year as they suffer large seasonal changes which have implications ranging across atmospheric warming, GHG emissions, release of fresh water and effects on vegetation. In addition, it is becoming increasingly important to measure the internal properties of the snowpack since, for example, increasing incidence of winter freeze-thaw events is giving rise to ice layers in the snow, which affect animal grazing.

Spatial and temporal properties of vegetation

The response of vegetation to Arctic warming needs to be monitored on annual timescales, and the interaction with snow cover needs to be better understood. Warming combined with earlier loss of snow and availability of water is changing the length of the growing season. The phenological signals of vegetation becoming photosynthetically active after winter and its senescence in autumn need to be monitored since these are strong indicators of the changing productivity of plants and hence their role in the terrestrial carbon balance. Changes in plant communities are also occurring, with observed northward migration of shrubs; significant changes are expected on decadal time scales. Migration of tree species is likely to be much slower. Both types of change in plant distribution need to be monitored on annual to decadal scales.

The Arctic carbon balance

Northern wetlands are a major source of both carbon dioxide and methane to the atmosphere, with the balance between emissions of the two species depending strongly on the macro- and micro-scale soil moisture status. Drier soils allow oxidation and hence carbon dioxide emissions while saturated soils lead to anoxic decomposition and methane emissions. Both can occur in the same area due to micro-topographical variations. Observations of emissions of both species are needed at scales ranging from local to continental, and over the wide range of wetland types in the Arctic. Understanding the balance between the two also requires detailed mapping of the micro-topography in selected representative areas.

Permafrost and freeze-thaw cycles

Because of its importance as a huge reservoir of locked-up but potentially labile carbon, permafrost must be monitored on annual timescales to understand its dynamics under climate warming. The quantities to be measured include the active layer depth and the permafrost temperature. Active layer depth is particularly important because it is related to water dynamics in the soil. Since water cannot penetrate the upper level of permafrost, the depth of the active layer can give rise to a perched water table which controls the availability of liquid water for plants and hence their possible rooting depth. The extent of permafrost is also obviously of interest. Permafrost state and dynamics are influenced by climate, but also very much by local geographical and ecological conditions. To improve our understanding of permafrost change, in particular with respect to the carbon balance and its socio-economic consequences, there is an urgent need for denser observational networks covering a wide range of environmental and climatic conditions. The annual cycle of surface freeze-thaw is a related process that needs to be measured at pan-Arctic scale using satellite microwave sensors.

Soil moisture and surface water

Monitoring of soil moisture is crucially important because of its role in plant productivity, the balance between methane and carbon dioxide emissions, and freshwater runoff. An important link is that between soil moisture and the freezing and thawing of soil, which controls the availability of liquid water that can be exploited by plants for growth. A related observable is the seasonal occurrence of surface water as small lakes, because of their potential importance for GHG emissions.

The export of fresh water and nutrients into the Arctic Ocean

Because northward flowing rivers provide a major source of freshwater and nutrients to the Arctic ocean, particularly in the Eurasian sector, it is essential to measure the long-term behaviour of this runoff and its nutrient load in order to understand its impact on the physical and biological enviroment of the Arctic Ocean and the productivity of its coastal zone. The quantities required are mean daily discharge data from all major Arctic river basins draining into the Arctic Ocean, possibly supplemented by upriver measurements of water level and flow velocity. Estimates of Dissolved Organic Carbon and other nutrients would also be very valuable.

Terrestrial and freshwater ecosystems

GEOBON (Group on Earth Observations Biodiversity Observation Network) has identified 22 Essential Biodiversity Variables (http://geobon.org/essential-biodiversity-variables/classes/). Among those, the variables that are of particular relevance to observe in terrestrial and freshwater ecosystems of the Arctic include: species distribution, population abundance and population structure by age/size class (e.g. reindeer/caribou, musk ox, freshwater fish), phenology (migratory species like reindeer/caribou and geese), primary productivity (vegetation), and secondary productivity (i.e. meat, fish, shellfish and other products derived from terrestrial areas and freshwater wetlands). Some of these variables are most effectively monitored through partnerships that involve both scientists and local stakeholders (see https://www.caff.is/community-based-monitoring; Chandler et al. 2016). In Section 5.6, we further discuss community-based observing systems.

4.3 CRYOSPHERE

A number of international, coordinated efforts attempt to collect, host and present a range of cryospheric essential variables, helping users worldwide getting access to data and define evolving user requirements. The Global Terrestrial Network for Glaciers (GTN-G) (http://gtn-g.org/) is the framework for the internationally coordinated monitoring of glaciers and ice caps in support of the United Nations Framework Convention on Climate Change (UNFCCC). Other relevant sites hosting cryospheric essential climate variables are the Global Terrestrial Network for Permafrost (http://gtnp.arcticportal.org/), the ESA CCI (http://cci.esa.int/) and the Copernicus Climate Change Service (https://climate.copernicus.eu/).

Essential in situ/near surface variables

Basic data, such as fjord bathymetry and glacier trough depths are challenging to obtain, yet essential in order to model the ice-ocean interaction. As novel methods and large-scale airborne, satellite and in-situ campaigns slowly start to fill this gap, observations of the ocean and ice becomes increasingly relevant and useful. The ESA Sentinel satellites servicing the EU Copernicus Programme is opening new possibilities for monitoring of the ice-ocean interaction by enabling tracking of velocity changes and ice front positions on a weekly scale.

Ice velocity and ice elevation are useful for the corresponding satellite-derived ECV's to increase the understanding of ice-dynamics. Other highly valuable observations conducted at the surface of the ice sheets or glaciers relate to surface mass balance and the connection to the atmosphere and climate system, such as surface albedo, longwave radiation, surface and sub-surface temperature, 2m air temperature, barometric pressure, wind speed and direction, relative humidity and precipitation. All these serve the purpose of monitoring key processes at the ice/atmosphere boundary and establish a benchmark for regional climate models attempting to estimate the past, present and future surface mass balance. The direct measurement of the ice sheet/glacier surface mass balance is a requirement for testing model output, although it is difficult to obtain in the extreme and highly variable environment of an ice surface in the Arctic. Figure 4-1 shows an illustrative example of increasing net ablation (ie. mass loss) at the PROMICE weather stations on the Greenland ice sheet margin.

Airborne measurements are a type of near-surface observation that enables the coverage of larger regions, often linking fixed-point observations to satellite data. Systematic airborne campaigns have been conducted intermittently over the last 80 years in the Arctic mostly providing oblique/aerial photos and in more recent decades, observations of ice thickness with radar and elevation with laser altimetry. Airborne campaigns are increasingly making it possible to measure accumulation rates in the interior of ice sheets, especially when supported by in situ observations on the ice sheet surface – an essential variable needed to obtain the total mass balance of ice sheets and ice caps in the Arctic and thus the contribution to global sea level rise.

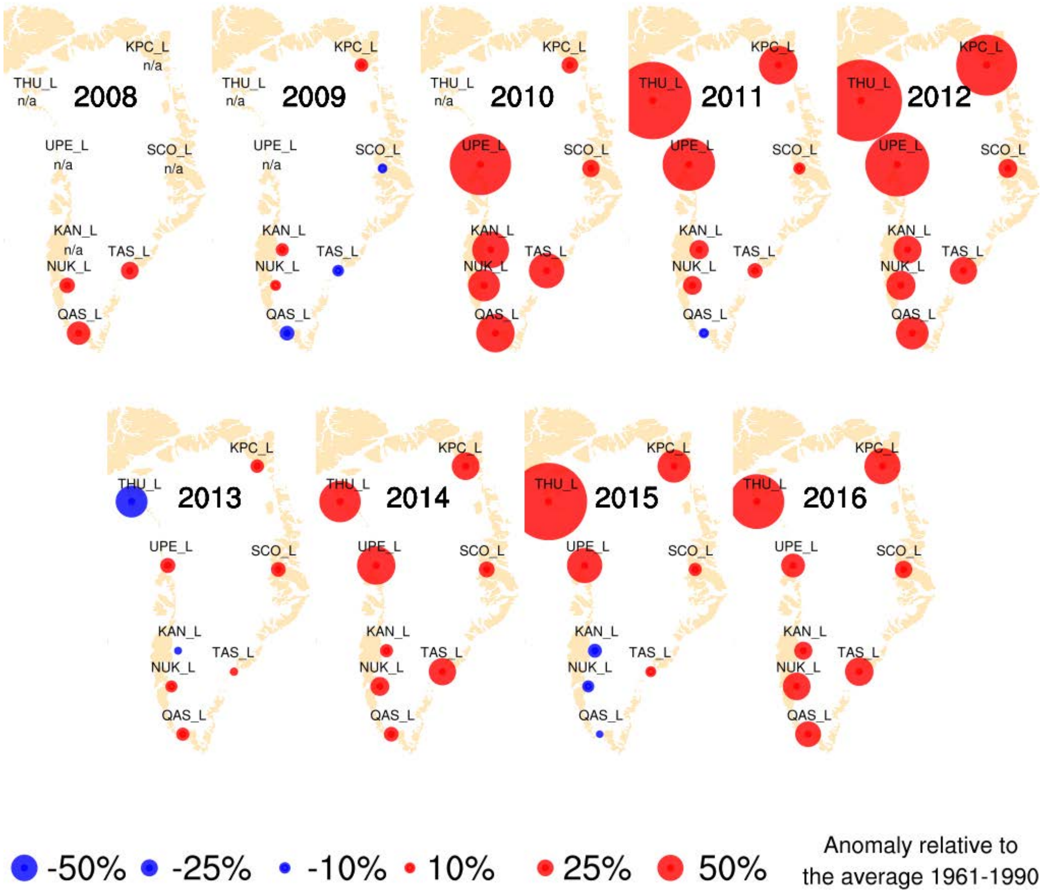


Figure 4-1 Net ablation anomalies at the ice sheet margin for 2008-2016, referenced to the 1961-1990 standard climate period following Van As et al. (2016b).

Essential satellite-derived variables

A useful user requirement survey (Hvidberg et al. 2016) was recently conducted for the following non-exhaustive subset of remotely sensed essential climate variables (as defined by the Global Climate Observation System, GCOS Satellite Supplement 2011): Surface Elevation Change (SEC), Ice Velocity (IV), Grounding Line Location (GLL), Calving Front Location (CFL), Gravimetric Mass Balance (GMB).

The user requirements found are listed in the table below:

	SEC	IV	GMB	GLL	CFL
MINIMUM spatial resolution	1-5km	100m-1km	100 km	100m-1km	100m-500m
OPTIMUM spatial resolution	<500m	50m	50 km	50m	50m
MINIMUM temporal resolution	annual	annual	annual	annual	annual
OPTIMUM temporal resolution	monthly	monthly	monthly	monthly	monthly
MINIMUM accuracy	0.1-0.5m/yr	30m/yr	-	-	-
OPTIMUM accuracy	<0.1 m/yr	10m/yr	20 Gt	-	-
What times are observations needed	all year	all year	all year	all year	all year

Table 4-1 User requirements for selected essential climate variable parameters.

Summary of user recommendations for these five ECV's:

1. The preferred priority by users is to have low resolution in the interior areas and a high resolution in the margin areas for both SEC and IV. (other scenarios are also useful).
2. The regions of special interest include glaciers all around the margin of the GrIS, in particular focusing on the major fast-flowing ice streams and glacier systems: Jakobshavn Ice Stream, Helheim Glacier, Petermann Glacier, and Nuuk Fjord Glaciers.
3. Open access to data is critical. ESA could use NSIDC or similar resources, as also recommended by GCOS. If not, users will continue using publicly available datasets.
4. High-level datasets are needed, in particular for climate and ice flow modellers who have no special knowledge of satellite-based data.
5. NetCDF (CF-compliant) is by far the most popular choice, in particular by modellers, although there is also a request for simpler file formats. Most users use Matlab or Fortran as their preferred software.
6. Long and continuous records are needed, in particular for SEC. Ensuring long-lasting records, is an important issue and must be taken into account when planning future satellite missions.

Apart from the five ECV's evaluated above, the surface broadband albedo and surface temperature are two additional essential climate variables observed from satellites. These are important in order to improve climate models and to observe essential climate system mechanisms such as the temperature-albedo feedback.

4.4 SEA ICE

Similar as for the atmosphere, also for sea ice it depends on the intended purpose which variables are required. Also the categories are similar to the atmospheric case. For operational sea ice charts, ice concentration, type, drift and thickness are the basic variables. Determination of sea ice thickness from altimeters in turn requires snow depth on sea ice. The sea ice floe size, and especially statistics on them, is required to estimate the interaction forces with technical structures like ships and offshore structures.

For numerical sea ice prediction on the scale from days to months and for climate models, in addition sea ice albedo, among other implicitly containing the melt pond fraction, are required. In numerical weather prediction models, sea ice is mostly a static variable.

More quantities are required for model validation, such as sea ice drift and age.

In order to cover the whole extent of the arctic sea ice varying between 4 and 16 km^2, satellite observations are the means of the choice. The required variables are determined from satellite observation in an inversion procedure. The results need

4.5 OCEAN

Essential Ocean Variables (EOVs) are the fundamental physical, biogeochemical, and biological measurements required to understand ocean phenomena well enough to provide applications that support Societal Benefits. More specifically, an EOV is a sustained measurement or group of measurements necessary to assess ocean state and change of a global nature, universally applicable to inform societal benefits from the ocean at local, regional, and global scales. EOV have so called sub-variables, which are components of the EOV that may be measured, derived or inferred from other elements of the relevant observing system and used to estimate the desired EOV. Supporting variables are other EOVs or other measurements from the observing system that may be needed to deliver the sub-variables of the EOV. Complementary variables are other EOVs that are necessary to fully interpret the phenomena or understand impacts on the EOV of natural and anthropogenic pressures. Derived products are calculated from the EOV and other relevant information, in response to user needs.

4.5.1 Physical EOVs

Ocean temperatures

Sea Surface Temperature (SST) exerts a major influence on the exchanges of energy, momentum, and gases between the ocean, sea-ice and atmosphere. These heat exchanges are a main driver of global weather systems. The spatial patterns of SST also reveal the structure of underlying ocean dynamics. Changes in subsurface temperature impact a variety of ocean services, including the growth rate, distribution, and abundance of marine species, including farmed and wild fish stocks. In addition, changes in subsurface temperature induce changes in the mixed-layer depth, the vertical and lateral ocean stratification, mixing rates, and currents.

Ocean salinity

Sea Surface Salinity (SSS) is a key parameter for monitoring the global water cycle (evaporation, precipitation, and glacier and river run-off) and observations over large scales can be used to infer long-term changes in the hydrological cycle and to quantify the evolution of the ocean in response to climate change. A subsurface salinity observing system is vital to close the global hydrological cycle and understand sea level change. Subsurface salinity observations, are required to calculate in situ density and ocean freshwater transports. In addition, changes in subsurface salinity induce changes in mixed-layer depth, vertical and lateral ocean density stratification, mixing rates, and currents.

Ocean Currents

Surface currents transport significant amounts of heat, salt, passive tracers, and ocean pollutants. On basin scales, zonal surface currents and their variations are key in climate to weather fluctuations. On smaller scales, surface currents contribute to vertical motion and mass exchange, and are important for accurate marine sea state forecasts, search and rescue, and oil spill modelling. Observations of subsurface ocean velocity are needed to estimate oceanic transport of mass, heat, freshwater, and other properties on local to global scales, and are particularly important in resolving the complex velocity structure of the major boundary currents, at the sea floor, near the equator, in ocean eddies, and in waves. Velocity profile information is also used to estimate ocean mixing. As the distribution of many life forms, including early life stages of commercially important fish, depend on transportation by currents understanding of ocean currents is important also for understanding marine ecosystems.

Ocean Heat Fluxes

Oceanic heat carried by northward-flowing waters in the Bering Strait, and especially in Fram Strait and the Barents Sea, strongly influence Arctic Ocean sea-ice distribution, ocean–atmosphere exchanges, and pan-Arctic temperatures.

Sea Ice

Energy budgets are heavily impacted by ice formation and melting and the presence or absence of ice cover (albedo, evaporation). Ice formation and melting modifies surface salinity, altering stratification and local circulation. Changes in roughness between ice and water impacts differential stress, and are related to relatively strong vertical motions and transports near the ice edge.

4.5.2 Biogeochemical EOVs

Oxygen

Sub-surface oxygen concentrations in the ocean everywhere reflect a balance between supply via circulation and ventilation and consumption by respiratory processes. The large (mostly) decreasing trends in the concentrations of dissolved oxygen over the last few decades affect marine species, including fisheries, and impact our understanding of anthropogenic climate change.

Nutrients

The availability of inorganic macronutrients (nitrate, phosphate, silica) in the upper ocean frequently limits and regulates the amount of organic carbon fixed by phytoplankton. This is a key control mechanism of primary productivity and thus of carbon and biogeochemical cycling. Measuring nutrient concentrations in coastal waters provides information for deriving indicators of eutrophication status.

Inorganic Carbon

There are four components of the inorganic carbon EOV: dissolved inorganic carbon (DIC), total alkalinity, partial pressure of carbon dioxide (pCO_2) and pH. The carbon system is in a delicate balance such that high quality, high-resolution and long-term observations are required to estimate changes in ocean acidification, anthropogenic carbon flux and storage, and to distinguish climate change-driven trends from seasonal to decadal variability in these and other processes.

Dissolved Organic Carbon (DOC)

DOC is one of the largest pools of bio-reactive carbon in the ocean, second only to dissolved inorganic carbon, exceeding the inventory of organic particles by 200-fold. Comparable in size to atmospheric CO_2, it is a crucial reservoir in the ocean carbon and nitrogen cycles, as well as in climate variations over long time scales.

Suspended Particulates

These include particulate organic matter (POM), i.e., particulate organic carbon (POC) and particulate organic nitrogen (PON), but also particulate inorganic carbon (PIC) and biogenic silica (BSi) as well as the vertical transport (export) flux of all particulates. Observations enable us to determine changes in the ocean's biomass, productivity, and acidification, as well as in water quality.

4.5.3 Biological EOVs

Primary Production

So far, most studies on primary production relied on remote sensing, which will remain a key component of future monitoring systems. However, this approach should be complemented by observations of at least chlorophyll a concentration at depth, which would act as ground-truthing of remote sensing PP estimates. Observations of benthic production should be made at selected sites.

Secondary production

The variable productivity of zooplankton influences many fish stocks and fisheries. Furthermore, zooplankton can limit the growth of blooms by grazing on protozoa and phytoplankton. They have a key role in defining the chemistry of the ocean as nutrients and carbon recyclers in near-surface waters and by delivering these materials to deeper waters (through defecation and vertical migrations). They produce fast-sinking faecal pellets which export carbon from the surface layers to the bottom layers of the oceans.

Fish abundance and distribution

Fish and fisheries are essential to ecosystems, economies and societies. Fish constitute the largest and most diverse group of marine vertebrates. They feed on lower trophic level organisms, including plankton and other fish, and are consumed by marine mammals, seabirds, fish, invertebrates, and microorganisms. For the main fish species, EOVs include abundance (number) and biomass. For well-monitored fish stocks, further information includes weight and numbers per age group and biomass of the mature part of the population (spawning stock biomass). Especially the latter provides valuable information towards estimating recruitment (the number of new fish to enter the fisheries).

Marine Mammals and Polar Bears

Large-bodied and relatively long-lived mammals have a key role in maintaining the health of ecosystems. Most species are vulnerable to human impacts such as fisheries (e.g., through reduction of their prey species and incidental capture in fishing gear) and climate change (e.g., reduction of habitat for arctic species) and provide longer term indicators of ecosystem health. Due to their position in the food web, they are affected by toxins and contaminants that accumulate up the food chain and therefore can act as sentinels for human health risks.

Marine Biodiversity

For the monitoring of biodiversity (in a broad sense including both specific species and habitats such as cold-water corals) working groups under CAFF have defined key areas of missing observations. Community wide monitoring to assess invasive species and changes in species range is highly valuable towards understanding biological effects of climate change.

The GOOS Biology and Ecosystems Panel is in the process of analysing 24 global and regional agreements or international bodies that identify the need for sustained monitoring of ocean ecosystems or biological variables, to extract the key drivers for observations and the pressures identified of human impact on marine biodiversity and ecosystem health. Their concept is to use a Drivers-Pressures-State-Impact-Response (DIPSIR) framework to identify the requirements for sustained monitoring of biological and ecosystems EOVs.

5. OBSERVING TECHNOLOGY/PLATFORMS

5.1 ATMOSPHERE

The vast majority of all operational observation stations are based on the land surface; very few, but somewhat strategically located, of these are so-called super-sites where more advanced data is also collected. Most, but not all, of the Arctic-relevant super-sites are located near the coast to the Arctic Ocean.

The Earth surface is, however, mostly ocean, so a significant amount of observations are therefore taken on ships. A very few of those, mainly icebreakers, makes into the Arctic, mainly in summer. The only reasonable way to obtain detailed sustained (over time) atmospheric information from the Arctic Ocean is from research icebreakers, such as in Europe the Polarstern (Germany) and the Oden (Sweden). It should be made mandatory to perform a minimum of observations from all ships in the Arctic, and strongly encouraged to carry observation stations on ships of opportunity. Radiosundings should be performed on all research vessels, regardless of research mission.

Routine surface observations besides from ships can also be obtained from drifting buoys; some of these on the Arctic already today provide surface pressure data (see Figure 3-1). For more sophisticated observations, for wind, temperature and moisture, and even more for energy fluxes, the harsh environment poses a major problem. Any passive instrument exposed to the atmosphere in the Arctic sooner or later experience deposition of water, either by deposition or riming, and becomes useless. Somewhat paradoxically, instruments in the ocean fares much better than instruments in the atmosphere. Currently the only way to get around this problem is by heating instruments, which requires power that is typically not available at autonomous instrument sites. There is an urgent need for technological development to get around this problem.

Operational manned aircraft observations are dependent on aircrafts of opportunity in the Arctic is unlikely to increase, and will only do so if commercial airlines increase trans-Arctic flights; this has its own set of problems. Other manned aircraft operations in the Arctic is by dedicated research aircraft. Some agencies have on occasion operated such experiments in the Arctic, but no long-term coordination exist. Experiments evolve on a project by project basis.

Instead the use of unmanned aircrafts (UAVs) is under rapid development. Two strategies seem to exist; one requiring large airframes for high payload and one favouring small airframes but with small payloads. Large UAVs are expensive and complicated to operate, and usually can only be used by large national or international organizations. They have the capacity and endurance to fly high in the atmosphere across the Arctic; this could be used to drop so-called dropsondes (an “upside-down” companion to the balloon-borne radiosoundings, falling under a parachute after release from aircraft). If this could be repeated on a daily basis, it would revolutionize weather forecasting. Small and inexpensive airframes for easier and more flexible use is rapidly evolving, primarily through miniaturization of instruments. These can be operated by smaller organizations. A large obstacle here is civilian flight rules, that makes operation of UAVs in controlled airspace very difficult; often impossible.

The last but probably most important type of platform is satellites. It is difficult to imagine any long-term pan-Arctic monitoring program that was not relying on satellites. As mentioned earlier, polar-orbiting satellites all pass over the Arctic twice per day. For orbital reasons, they all bypass the North Pole, and depending on the width of the observational swath, there may be a “hole” in the cover over the Pole, the size of which varies from satellite to satellite, and from instrument to instrument. Satellites measure radiation at different wavelengths; nothing else. Most satellites have passive sensors, measuring naturally occurring radiation, but a few have active sensors (radars & lidars). The information from satellites can either be assimilated as it is, like with the ECMWF/IFS, or it can be converted to proxy-observations by retrievals. While satellites in the Arctic has mostly been used to observe the surface, and in particular sea ice, new passive satellite instruments show promise to be able to provide reasonably high-resolution information on temperature and moisture. The problem as always is clouds; especially in winter, when the number of passive wavelengths are limited since the sun is down, it remains difficult to distinguish the top of low clouds from the ice surface.

5.2 TERRESTIAL

Observing the key variables in the terrestrial Arctic requires a wide range of satellite- and ground-based instrumentation, supplemented in some cases by airborne measurements. With the exception of in situ measurements of GHGs, all variables of interest to the terrestrial domain and means to measure them are dealt with in the Global Climate Observing System Implementation Plan (2016). The sections below therefore exploit the information to be found there, but with comments specific to the Arctic, together with a section on in situ measurements of GHGs. Community-based observing systems as platforms for monitoring are discussed in Section 5.6.

Spatial and temporal properties of snow

The primary source of information on the large-scale properties of snow is from satellite data, with medium resolution optical instruments, supplemented by microwave data, providing regular maps of snow covered area, while microwave radiometers are the main source of information on snow water equivalent, and hence implicitly on snow depth and snow density. Airborne lidars are also capable of providing snow depth at regional scale, and in situ measurements are supported by several nations. There are longstanding major activities aimed at providing global information on snow, notably through the National Snow and Ice Data Center (NSIDC, Boulder, Co.) and more recently by the European Space Agency (the GlobSnow project).

Spatial and temporal properties of vegetation

Large scale information on vegetation cover and phenology is almost exclusively provided by 10-30 m resolution satellite imagery (Landsat type) or coarser 250-1000 m data of MODIS/MERIS/AVHRR type (Stow et al., 2004). This is supplemented by limited in situ observations mainly for training and validation purposes. While accuracies of 95% are claimed for global land cover classification, the accuracy for relevant Arctic cover types is not well-documented, nor is the accuracy of Arctic land cover change. Similarly, the ability to detect the phenology of Arctic vegetation from space is not well known and in situ data appear essential to monitor this process. Monitoring of vegetation activity using Leaf Area Index (LAI), fAPAR and associated estimates of plant phenology is possible using optical satellite data. An important source of information on in situ conditions is the International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT), which aims to build capacity for identifying, understanding, predicting and responding to diverse environmental changes throughout the wide environmental and land-use envelopes of the Arctic. It currently involves 77 terrestrial field bases in northern Europe, Russia, US, Canada, Greenland, Iceland, the Faroe Islands and Scotland as well as stations in northern alpine areas, and includes projects within the fields of glaciology, permafrost, climate, ecology, biodiversity and biogeochemical cycling.

The Arctic carbon balance

The primary information on carbon dioxide and methane emissions to the atmosphere in the Arctic is from very sparse in situ measurements using flux towers, together with sensors carried on light aircraft. Currently 31 flux towers are known to be operating in the Arctic, of which only 8 exist in the huge Eurasian sector. The coverage in Alaska is shown in Fig. 5-1. Almost all of these towers are registered with the Fluxnet network (https://fluxnet. fluxdata.org/), but this does not guarantee access to data. At continental scales, satellite observations from GOSAT and OCO, combined with atmospheric inversion, allow the temporal and spatial dynamics of emissions of carbon dioxide and methane to be mapped at very coarse scales. Important tools linking the bottom-up estimates of emissions with the top-down estimates from satellites are ecosystem models which can assimilate flux tower data combined with information on land cover and quantities such as LAI or fAPAR provided by satellites.

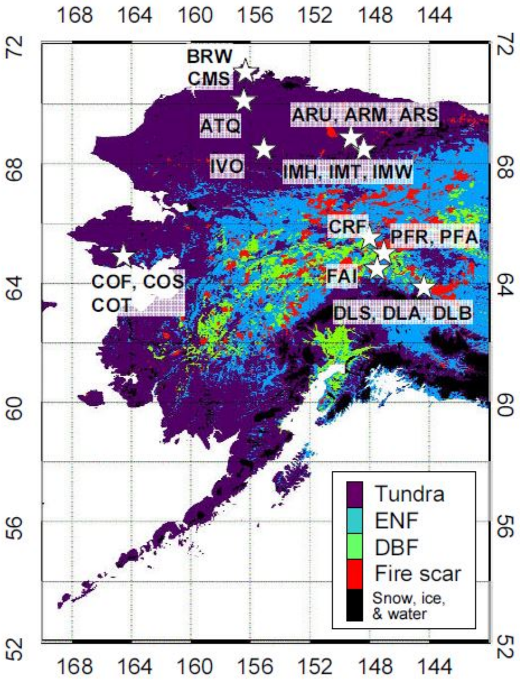


Figure 5-1 Flux tower sites in Alaska

Permafrost and freeze-thaw cycles

Measurement of permafrost properties is almost entirely reliant on in situ measurements, although relevant information on land cover, near-surface temperature, surface freeze-thaw and soil moisture can be provided by satellites (e.g., MODIS, Envisat and Sentinel-1, microwave radiometers). Coordination of national networks of in situ observations is being developed by the Global Terrestrial Network for Permafrost (GTN-P; http://ipa.arcticportal.org/products/gtn-p), building on initiatives to provide a circum-arctic synthesis and quantification of climate change impacts on permafrost stability and carbon turnover, such as the Circumpolar Active Layer Monitoring programme (CALM: http://ipa.arcticportal.org/activities/gtn-p/calm/16-calm). However, the current distribution of permafrost boreholes is not very representative and in many cases the available time series only covers a few years, so cannot provide strong statistical evidence on trends. Unlike permafrost, surface freeze-thaw can be measured using microwave scatterometers and SARs, allowing the variability and dynamics of this variable to be mapped since the early 1990's.

Soil moisture and surface water

The primary source of large-scale information on soil moisture and surface water is from satellite-borne microwave radiometers, scatterometers and synthetic aperture radars (SAR) in the 1-10 GHz range (L-, C-, and X-band) supported by medium resolution optical and thermal sensors. This is complemented by the International Soil Moisture Network (ISMN) of in situ measurements, but this network has effectively no presence in the Arctic. Under the aegis of GCOS, coordinated monitoring of soil moisture is led by the Global Terrestrial Network for Hydrology (GTN-H). Global coordination of a range of satellite observations of soil moisture to yield a unified soil moisture product has been a major achievement of the ESA CCI project on soil moisture.

The export of fresh water and nutrients into the Arctic Ocean

The primary source of information on river runoff into the Arctic (and elsewhere) is national in situ observations coordinated through the Global Terrestrial Network for Runoff (GTN-R) in an activity led by the Global Runoff Data Centre (http://www.bafg.de/GRDC/EN/Home/homepage_node.html), which is hosted in the German Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde) in Koblenz. Supplementary information on river levels is provided by satellite microwave altimeters. As far as is known, there are no systematic estimates of Dissolved Organic Carbon and other nutrients into the Arctic Ocean

5.3 CRYOSPHERE

Satellites form the backbone of glaciological observations in the Arctic, providing consistent, spatially distributed datasets often spanning decades. More recently, the multi-purpose satellite sensors have been supplemented with dedicated cryospheric missions, such as ICESat and CryoSat-2 targeting ice sheet elevation. Large-scale application of commercial satellite platforms is currently providing a new Arctic DEM at a spatial resolution of a few metres and the ESA Sentinel programme is launching a series of Earth observation satellites revolutionizing the glaciological observation capabilities of the ice sheets and glaciers in the Arctic and elsewhere.

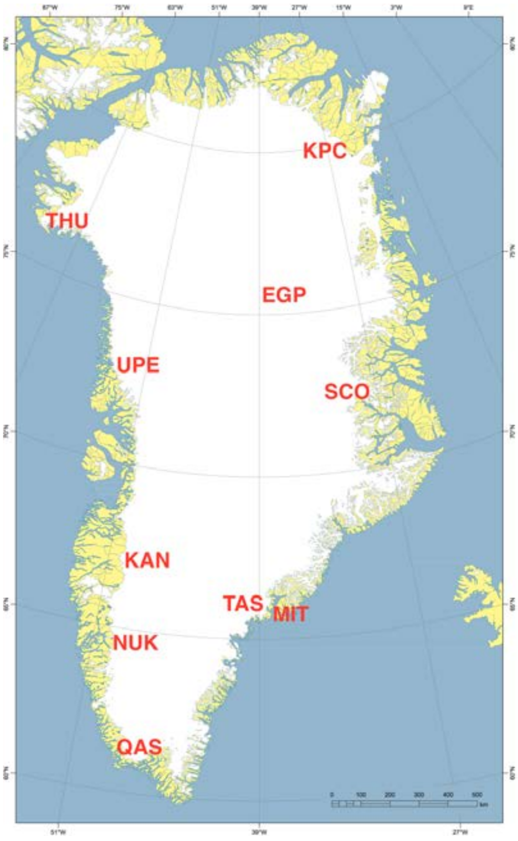


Figure 5-2 Map of Greenland with PROMICE automatic weather station regions indicated.

Airborne campaigns have provided large-scale coverage in the Arctic since the 1930s and is currently providing ice elevation and ice thickness over the Greenland ice sheet and ice caps in the Arctic region. These campaigns have also provided internal layering of the Greenland ice sheet. UAV’s are increasingly used, often for smaller scale studies conducted repeatedly over a field campaign.

Traverses over the ice sheet surface provide a platform for conducting in-situ observations over a larger region, such as accumulation measurements. They are especially useful for observation of parameters that do not change rapidly unless the campaign is designed to be concurrently overflown by airborne or satellite-borne missions.

Fixed location measurements are e.g. conducted from networks of automatic weather stations (see *Figure 5-3*) like the PROMICE network depicted in *Figure 5-2* and GC-Net both situated on the ice sheet surface, or from GPS stations like GNET placed on rock outside the ice sheet margin. Such networks are expensive to visit, but provide a useful platform for additional instrumentation.

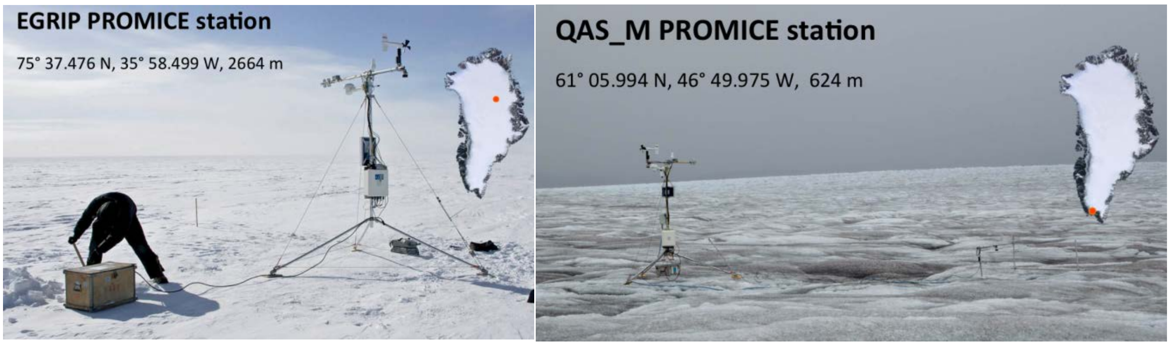


Figure 5-3 New PROMICE weather stations installed in 2016: EGP (left) and QAS_M (right).

5.4 SEA ICE

Clearly the most important observing platforms for Arctic sea ice are satellites on a nearly polar orbit. Most of them use a sun-synchroneous orbit in order to daily cover the whole globe. As a consequence, the orbit inclination cannot be exactly 90° so that the orbit does not lead exactly over the pole, and a circular region around the pole remains unobserved by most satellite sensors. For passive microwave sensors with a swath width of around 1200 km, this leads to a observation gap around the pole (Figure 2-25).

For sea ice concentration, type and drift, passive microwave sensors like AMSR2 and SSMIS with their ability of penetrating cloud and independence of daylight, and reliable retrievals, are most frequently used, sometimes together with scatterometer data which have similar resolution. For higher resolving information sea ice information, frequently SAR sensors like Sentinel-1 are used, but they do not cover the whole Arctic daily and require human interaction for analysis. Optical sensors lik Sentinel-3 cover the pole daily at ~1 km resloution, but are hampered by cloud and (polar) night. Higher resolving optical sensors do not observe daily, but are sui for case studies. Typically, with the resolution the observing frequency decreases. Very high resolving satellite data are not freely available, even for scientific purposes.

Sea ice thickness is retrieved for climatological applications is done from altimeter observations like Cryosat-2, and for thinner ice up to 1m by L-band microwave sensors like SMOS and SMAP.

For higher resoling observations for validation can be obtained from field campaigns, ships, and manned and unmanned aircraft as described in the Atmosphere section.

5.5 OCEAN

To implement an integrated Arctic Ocean observing system, the more theoretical ideas listed above must subsequently be translated into a well-coordinated set of observing platforms with sensors measuring EOVs, deployed appropriately to capture the needed space and time scales and accuracy required for the applications identified. The identified observing platforms and networks below are the in situ platforms and networks (platform-based groups coordinating on a basin scale) that are capable of primarily measuring physical and biogeochemical EOVs. Like for biological and ecosystem EOVs, the platforms and networks focused on biology and ecosystems monitoring in the high Arctic are still under identification and development.

Remote Sensing

An array of geostationary and polar-orbiting satellites operated by the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) sample the surface ocean on unprecedented spatial and temporal scales, providing basin-wide coverage with a simultaneous high spatial resolution on the order of kilometres. The inaccessibility and sheer size of sea ice covered regions in the Arctic Oceans make satellite remote sensing the only tool that can obtain a full picture of sea ice conditions. Remote sensing observations are also essential to studying surface processes related to organic matter cycling. Although much more challenging and associated with very large uncertainties, satellite observations may also provide information about changing carbon content in the continental shelf and marginal seas regions.

Aircrafts

Aircrafts are used to monitor and record interactions between the Earth's crust, ice- and snow-covered areas, oceans and the atmosphere. Objectives of aircraft missions are, for instance, high-resolution sea ice thickness measurements of first and multi-year sea ice as well as black carbon and trace gases measurements to study atmosphere processes in the Arctic. Aircrafts are also used for some biological observations, including determining the size of near-surface schools of fish by means of LIDAR (Light Detection And Ranging) and counting marine mammals on ice and.

Flying Drones

Pre-programmed surveys with Unmanned Aerial Vehicles (UAVs) could help scanning ice-covered areas for a number of different parameters (e.g., area-wide coverage of ice flows by melt ponds). Other applications for UAVs include surveys of floating (natural and human) debris or the determination of water column properties in ice-free areas of the Arctic Ocean. Recently, drones have been used to count seals.

Ship-based observations

Despite numerous technological advances over the last several decades, ship-based observation remains the only method for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. Repeated sampling during ship-based observations may include combined CTD (conductivity, temperature, depth) measurements and water sampling with the CTD/Rosette Water Sampler, bio-optical measurements in the upper water column, video plankton recorders (VPRs), plankton net sampling, pelagic and bottom trawling for fish as well as sediment coring at the seafloor. Towed camera systems are used to assess large-scale distribution patterns of larger epi-benthic organisms and other objects (e.g. dropstones, garbage) at the deep seafloor.

Underway measurements could be facilitated by so-called FerryBoxes, i.e., automated measurement systems used to determine physical and biogeochemical parameters in surface waters. Besides being installed on research vessels, they are mounted on 'ships of opportunity', such as ferries or container ships that serve regular routes or are operated as fixed installations. Water is pumped from a subsurface intake into the measuring circuit containing multiple sensors. Parameters determined by the systems usually include temperature, salinity, turbidity, chlorophyll, pH, oxygen, pCO_2, algal groups, and different nutrients. The automated regular recordings by the FerryBoxes enable detailed investigations of physical and biogeochemical processes and are, for instance, assimilated into models.

Ice-Tethered Platforms (ITP)

ITPs that perform autonomous measurements of physical properties of sea ice, snow, and the uppermost ocean are one of the main instruments to collect time-series data sets from the remote polar regions. These drifting instruments independently transmit their data via satellites, and enable observations over larger areas and over longer time periods than manned expeditions, even throughout the winter. Types of instruments combined in ITPs range from snow depth beacons and ice mass balance buoys for monitoring ice growth and snow accumulation, over radiation and weather stations for energy budget estimates, to ice-based profiling systems for upper ocean monitoring. Further, development of new bio-optical and biogeochemical buoys is expected to enhance our understanding of bio-physical processes associated with Arctic sea ice.

Drifting Buoys

Drifting buoys are generally attached to some form of drogue or sea-anchor, are easy to deploy, are relatively inexpensive to operate and reliably measure the atmosphere and ocean surface conditions, for an average of 18 months. Drifting buoys have a long history of use in oceanography, principally for the measurement of currents. Placed on the sea ice, they are used extensively in Arctic regions to track ice movement. Such buoys are equipped with low temperature electronics and lithium batteries that can operate at temperatures down to -50°C. In addition to the regularly-computed Argos locations the ice buoys can be equipped with satellite navigation receivers (e.g., GPS) which can compute even more accurate positions.

Profiling Floats

The critical capability of an Argo profiling float is its ability to rise and descend in the ocean on a programmed schedule. The floats do this by changing their effective density. The Argo float keeps its mass constant, but by altering its volume, it changes its density. To do this, mineral oil is forced out of the float's pressure case and expands a rubber bladder at the bottom end of the float. As the bladder expands, the float becomes less dense than seawater and rises to the surface. Upon finishing its tasks at the surface, the float withdraws the oil and descends again. Initially Argo floats were equipped with a CTD; advanced versions include a set of biochemical sensors. The deployment of Argo floats in the Arctic Ocean is restricted to ice-free regions.

Gliders

Underwater gliders have enhanced capabilities, when compared with profiling floats, by providing some level of manoeuvrability and hence position control. The gliders perform saw-tooth trajectories from the surface to depths of 1000-1500 m, along reprogrammable routes (using two-way communication via satellite), and can be operated for a few months. Their role in the integrated observing system is to fill the gaps left by other observing platforms. Gliders can operate at higher resolution than the ca. 300 km/10 day one of the Argo profiling float network, and the even sparser ship-based observations. Therefore, glider-based observations have an enormous potential to address regional and coastal issues, which are so important for societal applications. The deployment of gliders in the Arctic Ocean is restricted to ice-free regions.

Drifters

A drifter is an oceanographic device floating on the surface to investigate ocean currents and other parameters like temperature or salinity. They are typically tracked by satellite. Drifters provide real-time information about ocean circulation. They make more accurate and frequent observations of surface current velocity than is possible from remote sensing measurements. As for profiling floats and gliders, the deployment of drifters in the Arctic Ocean is restricted to ice-free regions.

Moorings carrying autonomous instruments

A mooring consists of up to several kilometres of Kevlar rope, on which various instruments are mounted at certain intervals. Buoyant floats attached to the rope keep the mooring almost vertical in the water column. They also force the mooring back to the surface upon release of the bottom weight. Releasers are situated right above the bottom weight. These instruments are mechanical actuators which will separate the mooring line from the bottom weight upon an acoustical signal sent by the mother ship. Moorings may be equipped with a variety of different oceanographic measuring and sampling devices, e.g., current meters, ADCP, oxygen and bio-optical sensors, autonomous water sampler, and sediment traps. Special moorings with an underwater winch as a top buoy carry a sensor platform capable to profile surface waters at pre-programmed time-intervals to register gradients in temperature, salinity, oxygen, carbon dioxide, and chlorophyll fluorescence in the upper water layers at high resolution. The profiler might be equipped with a satellite communication system to allow receiving "near real time" data from the study area. To impede damage of the sensor platform during periods of sea-ice coverage or in stormy weather conditions, these platforms should also carry a safety system, which will keep the profiler temporarily at depth.

Freefalling Systems (Benthic Lander)

A Benthic Lander is an unmanned vehicle that falls to the seafloor unattached to any cable, and then operates autonomously on the bottom. At the end of the deployment, ballast weights are released pre-programmed or on acoustic demand. The freefalling system floats back to the surface by its positive buoyancy. Benthic Lander can be used for different purposes and thus were equipped with different scientific modules, like current meters, respiration chambers, optical oxygen sensors, microprofiler, sediment traps and camera systems. Precautions must be taken to recover these freefalling systems in ice-covered areas.

Benthic Crawler

A benthic crawler consists of caterpillar drives, syntactic foam flotation devices, a large battery, a ballast release system and the scientific payload. Prototype systems carry benthic chambers or microprofiler systems for measuring oxygen gradients in the sediment, and high-resolution still cameras to document the probed area. Benthic Crawler can be deployed as freefalling systems or with pin-point accuracy by means of a video-controlled cabled launching system. When the ice conditions allow the recovery of the system, the ballast weight is released by an acoustic signal and crawler will ascend due to its positive buoyancy. Benthic Crawler allow repeated measurements and sampling for longer time periods (up to one year) to resolve seasonal variations in different parameters at the seafloor.

Autonomous Underwater Vehicles (AUVs)

AUVs are small, unmanned submarines. Most commonly these vehicles follow a preprogramed track consisting of several waypoints. On their way through the ocean they carry different instruments to measure several parameters from the temperature of the water to the amount of light penetrating the ocean. At the end of a mission the AUV and the supply vessel meet at a preprogramed position and the AUV is recovered. AUVs enable us to reach areas that are hard to access with conventional tools. They are able to sample horizontally close to the underside of the sea ice or just above the seafloor. The scientific payload they can carry depends on their size and the design of the vehicle.

Remotely Operated Vehicles (ROVs)

ROVs offer the opportunity to extend the vertical range of human exploration far beyond the reaches of conventional SCUBA-diving. Equipped with high-resolution cameras and sensor packages, these unmanned submersibles transmit their data via umbilical cable to the surface, allowing researchers and engineers to collect seafloor images and environmental information in real-time. Large, so-called "work class" deep-water ROVs, originally designed to serve industrial needs for off-shore production and intervention tasks, can be used for observations, targeted sampling, and experimental work at the seafloor.

5.6 Community-based observing systems

In all countries around the Arctic, there are community-based observing systems (Johnson et al. 2016). In this section, we present a spectrum of community-based observing approaches and we provide an example of results from a programme in Greenland. We also discuss the scope for connecting local and larger scale monitoring, the quality of information, the potential linkages to traditional and indigenous knowledge, and process-related challenges to community-based observing.

To understand the different uses and sources of community-based data on land and oceans in the Arctic, it is necessary to know the different kinds of community-based observing approaches that are used. These monitoring approaches range from programs involving local stakeholders only in data collection (citizen science) with the design, analysis and interpretation undertaken by professional researchers, to entirely autonomous monitoring schemes run by local people (Table 5-1; Danielsen et al. 2009).

Citizen science approaches where local stakeholders are involved only in data collection are particularly useful when large numbers of people are required to collect data across wide geographical areas and on a regular basis. This capitalizes on the strength of gathering the most data possible, even if the accuracy or precision of each individual data point may not be as high as that obtained by highly trained professionals. Monitoring approaches with more profound involvement of local stakeholders (the collaborative approaches in Table 5-1) are useful: (1) where local people have significant interests in natural resource use; (2) when the information generated can have an impact on how one can manage the resources and the monitoring can be integrated within the existing management regimes; and (3) when there are policies in place that enable decentralized decision-making.

To illustrate the potential uses of data from community based observing, we provide below an example from Greenland. The Greenland Government has piloted the development of a simple, field-based system for observing and managing resources developed specifically to enable Greenlandic fishers and hunters to document trends in living resources and to propose management decisions themselves (Danielsen et al. 2014). The system was designed to build upon existing informal observing methods and it includes most of the aspects that are believed to make knowledge generation initiatives ‘culturally appropriate’ (Pulsifer et al. 2011). At the national level in Greenland, there is considerable scope for collecting community member observations from this system and using them to track wider trends in the abundance of resources while at the same time increasing local people’s voice in higher-level decision-making (Table 5-2). Data from community-based observing could potentially be aggregated to generate larger-scale overviews of, for instance, species range and phenology, habitat condition, opportunities and threats, the impacts of management interventions and the delivery of benefits such as wildlife resources to the local communities from the natural ecosystems.

Category	Arctic examples	Description		
Fully autonomous local monitoring	Customary conservation regimes, e.g., in Canada (Ferguson et al. 1998, Moller et al. 2004)	The whole monitoring process – from design, to data collection, to analysis, and finally to use of data for management decisions – is carried out autonomously by local stakeholders	↑	Increasing role of local stakeholders
Collaborative monitoring with local data interpretation	Arctic Borderlands Ecological Knowledge Co-op, Canada (Eamer 2004); Community-based monitoring by Inuvialuit Settlement Region, Canada (Huntington 2011); Opening Doors to the Native Knowledge of the Nenets, Russia (www.arcticcbm.org); Piniakkanik Sumiiffinni Nalunaarsuineq (PISUNA), Greenland (Danielsen et al. 2014; www.pisuna.org)	Locally based monitoring involving local stakeholders in data collection, interpretation or analysis, and management decision making, although external scientists may provide advice and training. The original data collected by local people remain in the area being monitored, but copies of the data may be sent to professional researchers for in-depth or larger-scale analysis		
Collaborative monitoring with external data interpretation	Community Moose Monitoring Project, Canada (Gofman 2010); Integrated Ecosystem Management (ECORA), Russia (Larsen et al. 2011)	Local stakeholders involved in data collection and monitoring-based management decision making, but the design of the scheme and the data analysis and interpretation are undertaken by external scientists		
Externally driven monitoring with local data collectors	Environmental Observations of Seal Hunters, Finland (Gofman 2010); Fávllis Network, Norway (Gofman 2010); Monitoring of breeding eider *Somateria mollissima*, Greenland (Merkel 2010); The Piniarneq fisheries catch and hunting report database, Greenland	Local stakeholders involved only in data collection stage, with design, analysis and interpretation of monitoring results for decision-making being undertaken by professional researchers, generally far from the site		
Externally driven, researcher executed monitoring	Multiple scientist-executed natural resource monitoring schemes with no involvement of the local stakeholders	Design and implementation conducted entirely by professional scientists who are funded by external agencies and generally reside elsewhere		

Table 5-1 Arctic and sub-Arctic natural resource monitoring schemes across a spectrum of possible monitoring approaches based on the relative participation of different actors (modified from Danielsen et al. 2009; Huntington et al. 2013). The relative role of local stakeholders in the monitoring systems increases from bottom to top between the five categories of monitoring systems.

	Attributes	Percep-tions*	Scientists' assessments	Source of scientists' assessments*	Correspondence
Fish	Atlantic cod, D	‡	`Few data`	Siegstad 2011	N.a.
	Wolffish *spp.*, D	↑	↑/⇔	Siegstad 2012	(✔)
	Greenland halibut	↑	↓/⇔	Siegstad 2011; 2012	⦸
Marine mammals	Ringed seal	↓	`Few data`	Boertmann 2007; Rosing-Asvid 2010	N.a.
	Harp seal, D	↑	↑	Department of Fisheries and Oceans 2010; Rosing-Asvid 2010	✔
	Narwhale	‡	`Few data`	North Atlantic Marine Mammal Commission 2012	N.a.
	Humpback whale	↑	↑	Heide-Jørgensen *et al.* 2011	(✔)
	Minke whale, D	↑	↑	Heide-Jørgensen *et al.* 2010	(✔)
	Minke whale, U	⇔	`Few data`	No information	N.a.
Land mammals	Arctic fox, D	↑	`Few data`	Boertmann 2007	N.a.
	Caribou, N	⇔	⇔	Cuyler *et al.* 2005; Cuyler & Nymand 2011	✔
	Musk ox, L	‡	`Few data`	No information	N.a.
Birds	Snow goose, D	↑	↑	Boertman 2007	✔
	Greenland white-fronted goose, U	↓	↓	Boertmann 2007; Boyd & Fox 2008	✔
	Canada goose	↑	↑	Bennike 1990; Fox *et al.* 1996; Boertman 2007	✔
	Common eider	↑	↑	Chaulk *et al.* 2005; Merkel 2010	(✔)
	White-tailed eagle, D	↑	`Few data`	No information	N.a.
	Large gulls*, D	↑	`Few data`	Boertmann 2007	N.a.
	Arctic tern, D	↑	⇔	Boertmann 2007; Egevang & Frederiksen 2011	⦸
	Brünnich's guillemot, breeding	↓	↓	Burnham *et al.* 2005; Labansen & Merkel 2012	✔
	Little auk, D	↑	`Few data`	Egevang & Boertmann 2001; Boertmann 2007	N.a.
Other	Winter sea-ice*, U	↓	↓	Danish Meteorological Institute	✔
	Offshore ships, U	↑	↑	Arctic Marine Shipping Assessment 2009	(✔)
	Trawling, D	↑	`Few data`	No information	N.a.

Legend: ↑, increased abundance; ↓, declining abundance; ⇔, no major change in the abundance; ‡, increased abundance reported in some areas, decline in other areas; `Few data`, there are little or no abundance data available; ✔, correspondence between community members' and scientists' assessments; (✔), probable correspondence between community members' and scientists' assessments but the time, area and/or temporal/spatial scale of the assessments do not match; ⦸, no correspondence. D, Disko Bugt; L, Naternaq/Lersletten and Svartenhuk; N, Nassuttooq/Nordre Strømfjord; N.a., not applicable; U, Uummannaq Fjord.
*For latin names and details, see Danielsen et al. 2014.

Table 5-2 Comparison of community members' perceptions and trained scientists' assessments of trends in the abundance of 24 attributes in NW Greenland 2009-2011 (Danielsen et al. 2014).

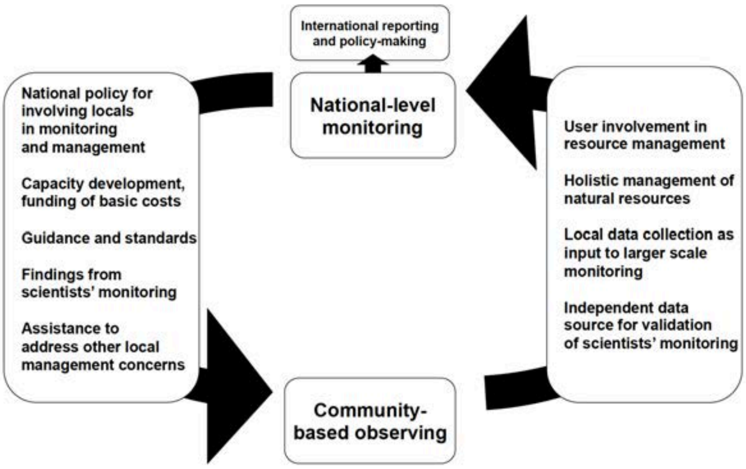
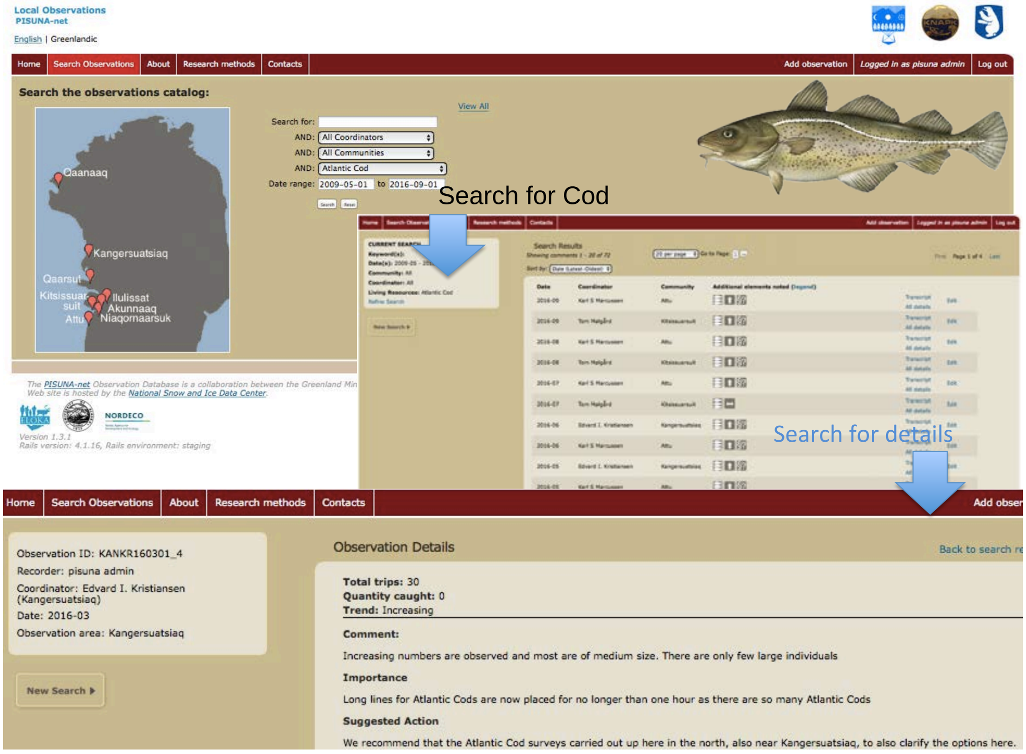


Figure 5-4 Contributions to, and benefits of, local monitoring for national-level monitoring of natural resources in Greenland (Danielsen et al. 2014; adjusted from Pratihast & Herold 2011, with permission).



Observation ID: KANKR160301_4
Recorder: pisuna admin
Coordinator: Edvard I. Kristiansen (Kangersuatsiaq)
Date: 2016-03
Observation area: Kangersuatsiaq

Observation Details

Total trips: 30
Quantity caught: 0
Trend: Increasing

Comment:

Increasing numbers are observed and most are of medium size. There are only few large individuals

Importance

Long lines for Atlantic Cods are now placed for no longer than one hour as there are so many Atlantic Cods

Suggested Action

We recommend that the Atlantic Cod surveys carried out up here in the north, also near Kangersuatsiaq, to also clarify the options here.

Figure 5-5 Screenshot of PISUNA-net, a web-based searchable, 'real-time' database comprising Greenlandic fishers and hunters knowledge and proposed management actions on living resources. PISUNA-net was developed by Greenland Ministry of Fisheries and Hunting, Greenland Fishers and Hunters Association, Qaasuitsup Municipality and NORDECO in cooperation with ELOKA and University of Alaska Fairbanks. Link: https://eloka-arctic.org/pisuna-net/.

The scope for linking local and larger-scale environmental monitoring may best be explained by thinking about contributions and relative benefits (Pratihast & Herold 2011). If there are not benefits for both sides, the local-national linkages are unlikely to be sustained. On the other hand, if both sides contribute and benefit, a situation can be created that can help to stimulate and sustain collaboration. In *Figure 5-4*, we conceptualize how communities could be linked to national environmental monitoring in the Arctic in a mutually beneficial way. If local community-based observing are to be transformed into a networked, national system, the central government would need to provide a policy that sets aside government staff time and funds, develop minimum requirements for local monitoring and establish a data infrastructure system so that locally-acquired data can be uploaded and made publicly-available subject to the approval of the data-providing community members, such as PISUNA-net in Greenland (*Figure 5-5*). In return, local monitoring could encourage community engagement in decision-making and holistic approaches to resource management, and contribute data to national policy-making (Sutherland et al. 2014).

As well as providing data to inform local management decisions, community-based observing has the potential to shed valuable light on environmental changes at national and even pan-Arctic scales. The Greenland example described above is one such system currently in development which has been explicitly designed to allow such upwards movement of data, and ultimately to permit larger scale analyses. To the extent that systems like this can be implemented and replicated, important Arctic monitoring gaps can be plugged, at relatively low cost, while at the same time increasing local people's input to higher-level decision-making.

Certain kinds of Arctic and national data gaps seem particularly well-suited to input from local schemes such as trends in species and populations (adapted from Danielsen et al. 2005). Turning to habitats, while the extent of some biomes is most efficiently monitored top-down, via remote-sensing, for many others habitat loss proceeds primarily via degradation (and loss of content) rather than wholesale conversion. This is for instance the case in grasslands, fragmented taiga forest landscapes, freshwater (ponds, lakes, streams, rivers) and marine habitats such as inter-tidal areas. Few large-scale programmes exist for tracking such changes in habitat condition, but meta-analytical techniques mean that data from diverse small-scale studies can be usefully synthesized to elucidate regional and potentially even pan-Arctic patterns. Data from community-based observing could also be aggregated to generate larger-scale overviews on threats (such as unregulated artisanal harvesting) operating at relatively small scales, and on the local impacts of management interventions.

But perhaps the greatest scope for local-derived inputs to large-scale measures of change is in tracking the delivery of goods and services from natural ecosystems. These form a prime focus of the Convention on Biological Diversity, yet are extremely hard to monitor using a top-down approach. Appropriate meta-analyses of locally-generated data on flows in benefits such as harvests of wild species, and reliable provision of clean water, offer particularly good opportunities for measuring ecosystem services at the pan-Arctic-level. Yet several steps must be taken for this considerable potential of community-based data to be realised.

Most importantly, for community-based information to be useful at larger scales, monitoring schemes will need to be established in more sites and regions, and the resulting data must be as unbiased and precise as possible. Results can also only be synthesized where many programmes have monitored the same attributes. They need not all use a single standardized technique – this would be difficult given the importance of the monitoring schemes being autonomous, and would preclude schemes from being responsive to local circumstances and needs. However, it is important that only a relatively small number of methods, each well replicated, is used across the set of studies to be analysed. Provided this is the case then meta-analytical techniques can be used to check (and if necessary adjust) for differences in results being due to differences in field methods.

Quality of information

Although many studies suggest that measurements by community members can compare well with closely similar measurements by scientists, nevertheless community-based observing approaches are in general likely to be more vulnerable than professional techniques to various sources of bias, which decrease their accuracy (defined as the closeness of the resulting measures to their true values; (Table 5-3a). Key potential problems include a lack of measurement experience on the part of observers (which often leads to over- or under-estimates of abundance and size); potential conflicts of interest (with recorders perhaps inadvertently providing data which are biased towards managers' preconceptions); a tendency, in the absence of careful documentation, for methods to drift over time, or for results to reflect long-term ('fossilized') perceptions more than current trends; and the potential for the spatial or temporal coverage of monitoring to be unrepresentative of the entire system of interest (Danielsen et al. 2005).

Besides accuracy, the utility of monitoring is limited by the precision of the results (that is, the closeness of repeated measures of the same quantity to each other; Table 5-3b, Sources of low precision (leading to high variance around the estimated true value of the attribute of interest) may include small sample sizes; overly thin or patchy temporal or spatial deployment of sampling effort; the physical loss of data; and the inconsistent application of methods, either through time or across observers. These problems can affect all perception- and sample-based monitoring but are likely to be a particular problem where financial or professional human resources are tightly limited (Danielsen et al. 2005).

In situations in which an abundance of resources may condition quotas or financial payments to communities, the local communities may have an incentive to report false positive trends in those natural resources so that they can continue to harvest the resources or to be paid, even though the resources may actually be declining. Periodic triangulation of the monitoring results will therefore be required although this is no different to any well-designed natural resource management initiative, whether the monitoring is implemented by communities, the government or the private sector.

Triangulation could be based on random spot checks in which a subset of the area is resampled using other monitors or other field methods (e.g., remote sensing). It could also be combined with a statistical analysis of the community-based data in order to search for anomalies or trends that are beyond the normal or expected range (Bird et al. 2014).

	Community-based observing	Scientist-executed monitoring
(a) Constraints to accuracy		
Lack of measurement experience	2	1
Conflict of interest	3	1
Inconsistent use of methods, across time or observers	3	1
”Fossilized” perceptions	1-2	0
Unrepresentative spatial or temporal spread of sampling effort	1-3	1
Poor identification, field or language skills	1-3	1-3
(b) Constraints to precision		
Small sample size	3	2
Poor temporal or spatial spread of sampling effort	1-3	1
Physical loss of data	2	1
Inconsistent use of methods, across time or observers	3	1

0 = not a problem; 1 = limited problem; 2 = potentially important problem; 3 = potentially serious constraint

Table 5-3 Key potential constraints to the accuracy and precision of community-based and scientist-executed environmental monitoring (Danielsen et al. 2005).

Community-based observing and traditional knowledge

Most declarations from the Ministerial Meetings of the Arctic Council emphasize the importance of using 'traditional knowledge' (Berkes et al. 2000) to address challenges in Arctic communities. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) which all Arctic countries except Iceland are members of has similar goals, i.e. “to bring (the) different knowledge systems, including indigenous knowledge systems, into the science-policy interface" (UNEP 2012a). The intentions of the Ministerial Declarations and IPBES will entail the articulation of indigenous and local knowledge (UNEP 2011; 2012b; Turnhout et al. 2012).

A key challenge is how to use information generated by different knowledge systems (Huntington 1998; Colfer et al. 2005) within synthetic environmental assessments at the science-policy interface such as within national or pan-Arctic environmental monitoring (Sutherland et al. 2014). Central to this is how to validate knowledge. While scientific knowledge is validated primarily through peer-review, other knowledge systems have different validation approaches (Tengö et al. 2014). Validation of information within knowledge systems is well-established, whereas validation across knowledge system is a major challenge (Tengö et al. 2014; 2017). Unidirectional scientific validation of other knowledge systems may compromise the integrity and complexity of the knowledge (Bohensky & Maru 2011; Gratani et al. 2011) and promotes power inequality between technocrats and communities (Nadasdy 1999; Bohensky et al. 2013). Alternatively, validation of community-based knowledge through a respectful process of collaboration between scientists and community members facilitates mutual learning and empowerment (Cullen-Unsworth et al. 2012).

Community-based observing has an important role. To participate in decision-making, indigenous people need to translate a well-founded knowledge base on their territories (Dallman et al. 2011; UNEP 2013) into a format where it can be heard (Ens et al. 2012). One potential solution to connect indigenous/local and scientific knowledge systems is with the use of community-based observing. For example, community-led focus groups who document and validate indigenous and local knowledge on natural resources could increase the information available for measuring status and trends in natural resources, while at the same time potentially contributing to the empowerment of indigenous and local communities in natural resource management (Danielsen et al. 2014).

While community-based observing approaches have great potential for articulating indigenous and local knowledge, the use of community observing approaches for connecting knowledge systems should not be rolled out uncritically. Information 'harvesting' must be avoided (Gamborg et al. 2012; Tengö et al. 2014). Representatives of indigenous and local communities should decide whether community-based observing approaches can help enable them be heard and be useful for documenting knowledge. This is in line with the UN Declaration on the Rights of Indigenous Peoples which states that development must take place in accordance with their 'Free, Prior and Informed Consent' (United Nations 2008). Also in development of community-based observing systems it should however be recognized that some of the indigenous and traditional knowledge can, due to its local-cultural context, be difficult to translate directly into multi-stakeholder environmental monitoring (Mustonen 2014).

Process-related challenges to community-based observing

There are also challenges of community-based observing related to the process (not the data) which we summarize below. One challenge is that government structures sometimes have difficulties in incorporating community information into government decision-making processes. Linked to this, another challenge is that if community members are involved in monitoring without having a real say in the management of the land- and seascape, then local interest in participation will fade away over time. It is also a challenge that some natural scientists remain skeptical about the reliability of citizens' assessments of the status of the environment. Likewise, some of the protagonists of indigenous and local knowledge do not accept integration of citizen- and scientist-executed, government-led monitoring of the environment. Finally, community based observing also has the challenge that the costs associated with this activity are often put more heavily on local stakeholders (community members and their organisations) than those of conventional monitoring schemes, and the local stakeholders have often limited ability to get access to finance to compensate the time they use on community based observing.

6. Summary of INTAROS Stakeholder workshop 05 May 2017

This first INTAROS Stakeholder workshop was organised by EuroGOOS Office in its premises in Avenue Louise 231, 1050 Brussels. Title of the workshop was **"Building long term observing systems in the Arctic – requirements and challenges".** The objective of the workshop was to review and discuss the requirements for observational data in the Arctic across thematic areas such as 1) Atmosphere, 2) Ocean and seafloor, 3) Sea ice, 4) Marine Ecosystem, 5) Terrestrial data, 6) Glaciology, 7) Natural hazards, and 8) Community-based monitoring.

Furthermore, the workshop elaborated on ways ahead to develop and operate long-term observing systems. Satellite earth observation data, especially through meteorological missions and the new Copernicus programme, has secured long-term funding and is therefore relative sustainable. However, most of the in situ data collected in the Arctic are funded by research projects with duration of a few years and are therefore not necessarily sustainable. The workshop is the first in a series of events under INTAROS to develop a Roadmap for building and maintaining sustainable Arctic observing systems. Key challenges that INTAROS will address during the project period are:

(1) Coordination and collaboration between data providers and stakeholders in the pan-Arctic region in order to better use existing systems and resources

(2) Improvement of the observing platforms and sensors, filling of gaps in the observing network and facilitate for year-round operation

(3) Data sampling, transmission, calibration, processing, archiving and retrieval of required variables and building distributed and connected databases

(4) How to develop sustainability of the observing systems

The workshop had about 30 invited attendees including 15 speakers who presented status of observing systems representing different scientific disciplines and application areas.

Christine Daae Olseng from Research Council of Norway, chair of SAON, presented an overview of Sustainable Arctic Observation Network (SAON). The mission of SAON as a high-level organsation is to support and strengthen the development of multinational engagement for sustained and coordinated pan-Arctic observing and_data sharing systems that serve societal needs, particularly related to environmental, social, economic and cultural issues.

Lars-Otto Reiersen, from AMAP secretariat, presented a history of main work conducted by the Arctic Monitoring and Assessment Programme from 1991 to present. AMAP is to a large extent based on funding from national programmes and international monitoring network. AMAP has played an important role to obtain EU-funding for Arctic observing systems, which is the background for INTAROS.

Henrik Steen Andersen from European Environment Agency, presented the role EEA as coordinator of the in situ component of the Copernicus Marine Services. Copernicus is a large European programme for monitoring and forecasting of the Earths environment, with focus on satellite Earth Observation data and modeling services: The in situ component is very limited and mainly based on national efforts and research projects.

Nicole Biebow, from AWI, is the leader of the EU-PolarNET project, a coordination action for European Polar research. Nicole presented results of stakeholder surveys and workshops to identify the stakeholders in the Arctic and their needs for observing systems.

Øystein Godøy, from Met Norway, presented status of Arctic data repositories and interoperability, where there are significant challenges and barriers to build an integrated Arctic Observing System that can manage distributed data across scientific disciplines and thematic application areas

Lisbeth Iversen, from NERSC, presented an example of ongoing studies on community based observing systems where requirements are based on local needs and challenges. In Longyearbyen, it is particularly snow avalanches and landslides that are most important to monitor and predict.

Thomas Jung, AWI, presented requirements for observations under the Year of Polar Prediction (YOPP) where the goal is to improve the prediction capabilities through enhanced modeling activities, where the EU APPLICATE project plays a key role.

Cathrine Lund Myhre from NILU presented status of research infrastructure and networks in the Arctic for observation of atmospheric composition for climate and air quality monitoring.

Antonio Reppucci from Mercator Ocean presented Copernicus Marine Environmental Monitoring Service (CMEMS) and the specific requirements for observations in the Polar regions. The Arctic component of CMEMS forecasting system is developed at NERSC.

Inigo Martinez from ICES presented the Arctic perspective of the International Council for Exploration of the Sea (ICES). ICES have members from 20 countries and is seeking integrated observations from the Arctic where data on oceanography, ecosystems and vulnerability factors are needed.

Michael Zemp from the World Glagiology Monitoring Service present needs and challenges related to long-term observation of glaciers and ice sheets in the Polar regions and world-wide.

Elmer Topp Jørgensen from Aarhus University presented INTERACT, which is a network of terrestrial platforms for research and monitoring in the Arctic and high mountains.

Attilio Gambardella, from the European Commission presented an overview of EU's polar research strategy and the wider context for the INTAROS project. An important event in 2018 will be the second Arctic Science Ministerial to be organized by EU and Germany, following up the first Arctic Science Ministerial in Washington in 2016.

Erik Buch from EuroGOOS, summarized the workshop and with recommendation for follow-up workshops later in the project.

7. Summary and conclusions

The ambition of this "Initial Requirement Report" is to define the high-level requirements of an integrated Arctic Observing System (iAOS) based on identification of the major societal drivers of a sustained observing system in the Arctic region, driven by issues affecting the entire area and expressed through international agreements (i.e. climate, environment, biodiversity, sustaining ecosystem services, improving the livelihoods of indigenous and local communities, support to maritime safety, etc.). The present report is based on knowledge collected from literature studies, projects, programmes and workshops, and cover an evaluation of feasibility, readiness, and impact to provide guidance on future network design. This deliverable will feed into the work of WP2 and WP3. In the last phase of the project, the requirements will be revisited to integrate the inputs gathered during the project period.

It has been decided to use the design concept outlined in the "Framework for Ocean Observations" (UNESCO 2012), which includes several logical steps:

1. Define the Requirements – societal demands for information to address specific questions.
2. Identify the Phenomena associated with the observing objectives that are linked to requirements
3. Identify the Essential Ocean Variables (EOV's) associated with the observing objectives
4. Use the existing observing infrastructure for data acquisition of the respective set of phenomena and EOVs
5. Use data to derive information that addresses specific question (point 1) which will provide a measure for the capacity of present observation system
6. If information cannot be derived perform a Gap analysis (data acquisition, product generation)
7. Ensure a "Fit for Purpose" system, enhanced and optimized observation system

The present report focusses only on step 1 to 4. Present capacities and gap analysis is an activity in WP2.

It has additionally been decided to focus on the individual thematic areas - meteorology, terrestrial, cryosphere, sea ice and ocean – separately with the purpose of capturing the special requirements, phenomena and essential variables to observe within each of them. It very well known that these thematic areas are closely interconnected and have different levels of maturity in scientific understanding of the phenomena, definitions of essential variables and observing capacity. It is therefore a big challenge to INTAROS to use the collected information to design an integrated multipurpose and multiplatform observations system to optimises efforts and costs.

Observations serve several purposes:

- Process studies to gain fundamental understanding of phenomena, processes and interrelationships, which is fundamental for development of reliable forecasting models
- Establish long timeseries of Essential variables at key locations to monitor variability and changes in the system
- To assimilate into as well as to validate models

The detailed analysis of phenomena and observation requirements for the entire region given in this report reveals the following conclusions:

- The Arctic is a region very sensitive to environmental changes. There is a very close interrelation and delicate balance between the five thematic areas (atmosphere, terrestrial, cryosphere, sea ice and ocean) especially in relation to solar energy retainment and radiation budget and hydrological cycle. This has a great impact on physical, chemical and biological processes in the area.

- Due to the hostile environment, there is a great lack of basic observations in the Arctic that can support scientific understanding of key processes. Most of the existing data are collected via time limited research project. This lack of process knowledge is reflected in big errors in forecasting models – operational as well as climate.
- It is therefore crucial to establish a sustained Integrated Arctic Observing System that in the short timeframe can increase fundamental scientific understanding of the complex and sensitive Arctic environment and in a longer timeframe can secure a robust basis for decision making to the benefit of the people living in the Arctic, the environment, the broader international society, and commercial activities.
- It is foreseen that a future Arctic observation system will rely heavily on satellite observations supplemented more traditional in-situ platforms. Especially the ocean will use several other platforms such as ships, profiling floats, gliders, moorings, AUV’s etc. to monitor the interior of the Arctic Ocean.
- In all countries around the Arctic, there are community based observing systems that represent a strong potential for further development. Existing activities shall form the natural basis for a future more intensive and integrated sustainable Arctic Observing System.
- A stakeholder workshop was held in Brussel on 5 May, organised by EuroGOOS, where status and challenges regarding development of Arctic Observing Systems were discussed. In addition to technical and logistical challenges, there are also organisational barriers to building and operating a multidisciplinary observing system. These issues will be addressed in follow-up workshops.

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