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Synoptic Arctic *Survey*

-a pan-Arctic Research Program

Science and Implementation Plan

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BEYOND THE SCOPE OF ANY SINGLE NATION

The SYNOPTIC ARCTIC SURVEY (SAS) is a bottom-up, researcher driven initiative that seeks to define the present state of the Arctic Ocean (Fig. 1) and understand the major ongoing transformations, with an emphasis on water masses, the marine ecosystems, and the carbon cycle. We posit that it will not be possible to assess either the consequences or the range of the ongoing changes unless necessary empirical data are collected, analyzed and understood in concert with each other.

This position can be justified by the fact that all compartments of the Arctic are changing faster than our joint ability not only to properly measure and document them, but also our collective ability to understand them. A fundamental premise for approaching, sampling and understanding the far-reaching changes in the Arctic Ocean is thus that observations should be synoptic across the ocean, which is beyond the scope of any single nation. The SAS will overcome this limitation.

The objective of the SAS is the multi-national, coordinated engagement of research vessels in the summer of 2020[1] in an unprecedented effort to jointly cover the Arctic Ocean with a set of full depth hydrographic, biogeochemical and biological sections (Fig. 2). This collection of empirical data on a Pan-Arctic scale requires the involvement of as many research vessels as possible, a set of core measurements, shared protocols and the usage of the best available technology. This initiative has so far been endorsed by the International Arctic Science Committee (IASC) marine working group and the University of the Arctic (UArctic).

It should be noted, though, that this single synoptic survey of the vast Arctic Ocean will not alone address all ongoing transformations, but must be combined with other field observations, process studies, and complimentary modeling activities. However, without the Synoptic Arctic Survey proposed here, it will be impossible to evaluate and parameterize processes in the correct reference frame and to assess the relevance of model outputs.

THE GOAL of the SAS is to generate an unmatched dataset that allows for a complete characterization of Arctic Ocean hydrography and circulation, organismal and ecosystem functioning and productivity, carbon uptake and ocean acidification. By comparison to historical data the SAS observations will also enable detection of change. However, the possibilities for doing so are clearly limited by the insufficient temporal and spatial coverage of existing data, in particular for the state of the carbon cycle and ecosystem. In this respect, the comprehensive dataset from the SAS will provide a unique and critically needed baseline for future studies as it will allow us to track climate change and its impacts as they unfold in the Arctic over the coming years, decades and centuries. It also will inform and better constrain biogeochemical modeling efforts that similarly seek to understand and predict change. The SAS-vision is that this will be the first of several decadal efforts to assess the state of the Arctic that will lead to understanding of the specific questions posed in this science plan. Both future generations of polar scientists, decision makers and the public will benefit from such a reference.

The historical LEGACY for SAS dates back to the Maud Expedition (1918-1925) when the acclaimed Norwegian scientist and explorer Harald Ulrik Sverdrup was scientifically responsible for the traverse of the Northeast Passage. With 100 years having passed since this legendary science endeavour, it is now becoming increasingly clear that there is a dire need to explain the New Arctic and its connectivity to lower latitudes. Providing cutting-edge insight on the uniquely coupled Arctic Ocean – its physical state, its ecosystems and carbon cycle – will mark a new era of polar research to the benefit of societies worldwide.

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[1] The final decision on the year of execution of SAS will be decided on the first meeting of its scientific steering group, planned for October 2018. For this document, 2020 is used.

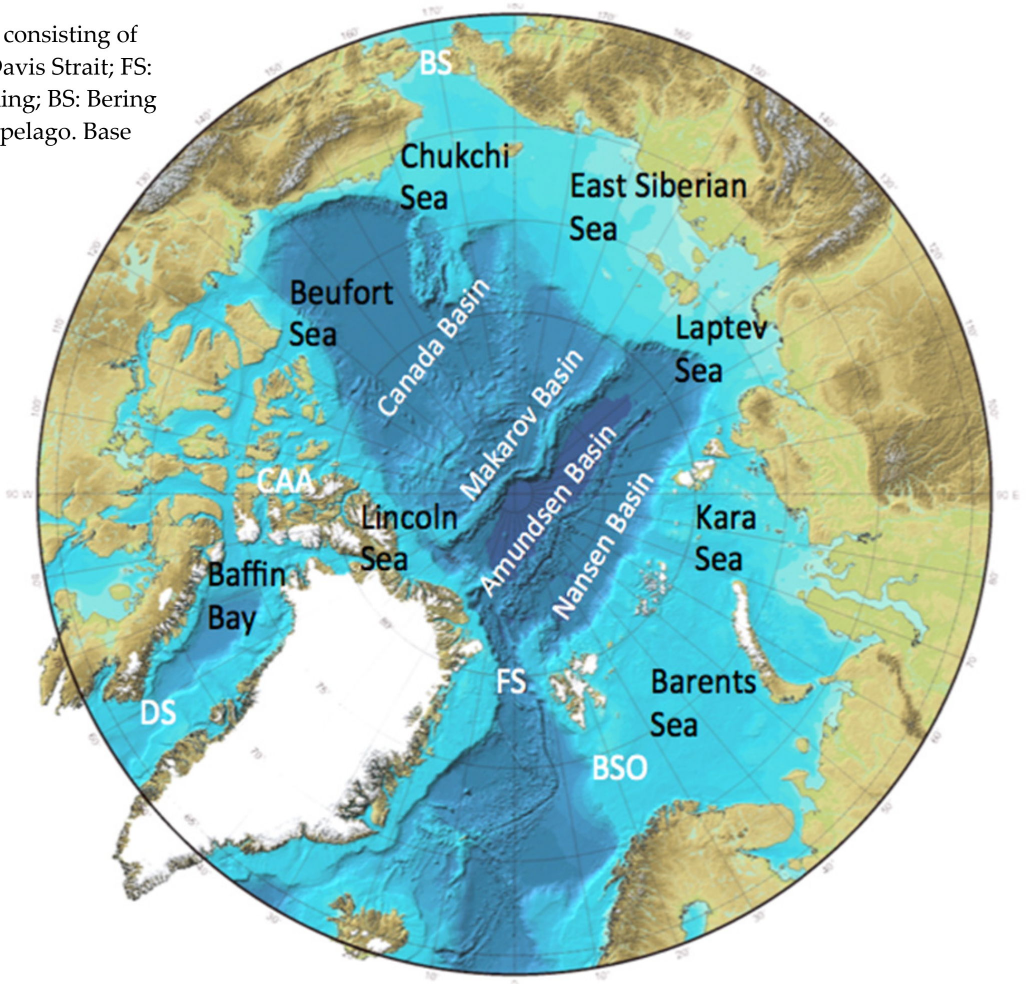


Figure 1. Map of the Arctic Ocean, consisting of the deep basis and shelf seas. DS: Davis Strait; FS: Fram Strait; BSO: Barents Sea Opening; BS: Bering Strait; CAA: Canadian Arctic Archipelago. Base map from *Jakobsson et al*. [2012].

INTRODUCTION

A New Arctic Ocean

«The field for future exploration is tremendous»

Scientific work of the Maud 1922-1925

Harald U. Sverdrup, 1926.

The Arctic Ocean (AO) is losing its iconic sea ice all too rapidly. Not as obvious but equally large changes are taking place beneath the ice/ocean interface where water masses and ocean life interact across a range of temporal and spatial scales. The AO, comprised of roughly half continental shelf and half deep basin and ridge complex, is an important and enigmatic sea to which scientists have been drawn for centuries. The ongoing transformation of this region now warrants new approaches and new knowledge as it becomes increasingly similar to other oceans. Change is occurring in all portions of the system, challenging any given research approach.

The recently increased seasonal opening of the AO exposes it to more sunlight and wind, altering fundamental boundary conditions. Basin boundaries and submarine ridges still define circulation pathways in overlying waters and limit exchange in deeper waters, but changes in freshwater supply from melting ice sheets, glaciers and run-off from great Siberian rivers influence mixing regimes along the shelf and lowers the overall salinity impacting ecosystems and the carbon cycle.

The AO is an integrated part of the global ocean. Pacific-origin water (PW) enters through Bering Strait into the Canada Basin and Atlantic-origin water (AW) through Fram Strait and across the Barents Sea into the Nansen Basin. Consequently, the AO plays two roles in the global ocean circulation - it provides an oceanic pathway from the Pacific to the Atlantic Ocean; and it modifies the Atlantic Water during its circulation in the AO and returns it partly at higher density to the Atlantic [*Rudels and Friedrich*, 2000]. These two pathways promote inputs and exchanges of heat, salt, nutrients, carbon and organisms between the Arctic and sub-Arctic.

There is a growing realization that the AO is not hydrographically static. Since the late 1980s there have been two prolonged episodes of significant warm anomalies in the Atlantic Water entering the AO [*Grotefendt et al.*, 1998; *Polyakov et al.*, 2005]. These warming episodes have been tracked in the Eurasian sector [*Dmitrenko et al.*, 2008]. Furthermore, the silicate maximum in the halocline of the Makarov Basin eroded abruptly in the mid-1980s, demonstrating that the redistribution of Pacific waters and the warming of the Atlantic layer [e.g., *McLaughlin et al.*, 1996] were distinct events.

Further important findings from decade-long time-series of *in situ* and remote sensing observations are the continued declines in sea ice extent and thickness [*Kwok and Rothrock*, 2009; *Stroeve et al.*, 2012; *Barber et al.*, 2015] and the increasing river discharges [*McClelland et al.*, 2006; *Prowse et al.*, 2016a, b]. The changes in sea ice conditions in turn accelerate warming, by reduced summer albedo and through the additional heat flux from the ocean as more open water areas are maintained later into the autumn. This positive feedback effect is known as "Arctic Amplification" [*Serreze and Barry*, 2011; *Makshtas et al.*, 2011; *Pithan and Mauritsen*, 2014] and is likely to strengthen in the years to come.

The interconnections between physical, chemical and (lower trophic) biological changes are slowly beginning to be incorporated into pan-Arctic conceptual models [*Wassmann et al.*, 2010 and 2015, 2010; *Slagstad et al.*, 2011]. Nevertheless, fundamental questions about AO circulation – as basic as water pathways and physical driving mechanisms – remain unanswered. Since Arctic forcing and inflows are changing as exemplified by the persistent warming events in Atlantic inflow to the AO [*Polyakov et al.*, 2005] and intermittent Pacific water warming [*Woodgate et al.*, 2007], tacit assumptions about stationarity in the AO are being revised, with more thought given to non-linear processes, which have gained traction in lower latitudes [*Lozier, 2010*]. One intriguing perspective on the AO is that, for the first time in recent history, a new ocean may be opening to the atmosphere [e.g., *Kinnard et al.*, 2011] - within a few decades or less the AO may see mostly ice-free summers extending fully across its basins.

A warming AO is already destabilizing glaciers, permafrost, and methane gas hydrates, but both rates and magnitude will probably increase. Changes in temperature, stratification, mixing and chemistry will also bring about fundamental challenges for AO ecosystems, at all levels. Ocean change will also alter sea -ice composition and extent, with numerous implications for climate, society and commerce. To successfully project future change in Arctic and quantify its implications, and to design an efficient observing system, we require a better understanding and quantification of dominant processes within the AO.

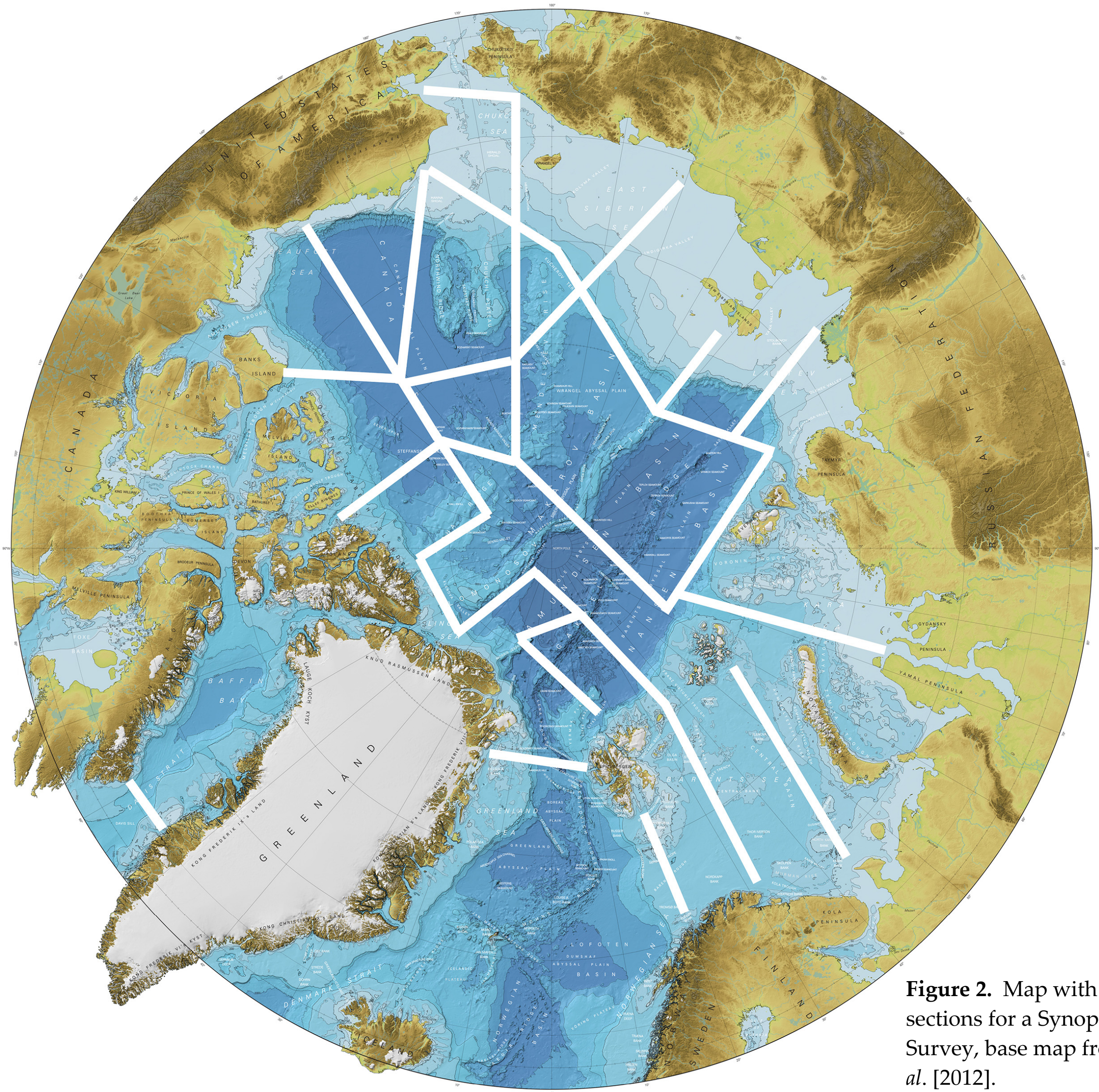


Figure 2. Map with tentative cruise sections for a Synoptic Arctic Survey, base map from *Jakobsson et al.* [2012].

A Leap Forward with the Synoptic Arctic Survey

The Arctic Ocean is an integrated part of the globe where changes at high latitudes propagate to lower latitudes and vice versa, but it is also interconnected across domains where shifts in the physical state of the water masses impact the ecosystems and carbon cycle. In turn, any major perturbation of the carbon cycle will feed back on the climate and the physical domain and ultimately to the marine ecosystem. The Arctic Ocean is currently changing faster than any ocean on earth and because it is the smallest of the world oceans, any change is rapidly communicated internally, whether driven by increased run off, fluctuating sea ice margins, shifts in wind patterns or ocean currents. This responsiveness is, in part, why changes manifest themselves so quickly.

Despite the fact that the central AO is relatively small, it has until recently been fairly inaccessible for both logistic (sea ice) and political reasons. Scientific cruises to, and in the AO, are expensive and often difficult to execute. Up to now, the Arctic has not been associated with substantial economic activity – a situation that has changed – which is perhaps why it has not been equally surveyed compared to other oceans. This is, for instance, evident from the oceanic coverage of the World Ocean Circulation Experiment [*King et al*., 2001].) WOCE was, according to Carl Wunsch (2005) the largest and most ambitious oceanographic experiment of its kind ever carried out. It took nearly 15 years to plan with 10 years of operation involving around 30 countries who covered costs equaling one gigadollars. This joint venture, which initially met fierce opposition, has revolutionized our understanding of the World's oceans based on an impressive data collection that has motivated and inspired the development of SAS. We believe that SAS connects strongly the global observation network and that the 'crisis' in oceanography that justified the realization of WOCE (cf. *Wunsch*, 2005) is in some ways are comparable to the challenges that the current transformation of the AO has cast on the scientific community.

In the AO, cruises and sections have been sporadically carried out by several nations through the years. These have produced unique snapshots of how the different biological, physical and chemical systems of the AO behave. However, these efforts, important as they have been, have typically been limited with respect to temporal and spatial resolution. Moreover, they have also tended to be discipline-based rather than being integrated multi-disciplinary efforts testing crosscutting hypotheses. For some characteristics, such as many carbon and, in particular, ecosystem parameters, comprehensive, trans-Arctic assessments covering multiple AO regions are highly irregular or have not even occurred in several decades, making quantification of changes difficult or impossible.

There are good and sound reasons why cruises historically have been conducted in this manner. It is cost-effective, the time needed to carry out respective measurements leaves little or no time to carry out other measurements, the study needs to focus on a specific region due to immediate science goals and so forth and so on. In short, the synoptic approach has been too demanding in terms of international collaboration, logistical and financial constraints, or even accessibility. National and international science campaigns actively seeking to explore connectivity across the carbon cycle, biological and physical systems have therefore been few in numbers. This is a serious shortcoming that SAS aims to overcome.

SAS will do this by providing a unique baseline of the AO summer conditions to which both historic and future observations can be compared. Importantly, this synoptic picture will reveal the spatial variability of the system to a larger extent than existing observations, and hence add to the understanding of its dynamics. In fact, the envisioned SAS data are a prerequisite for detecting changes of the many components of the AO system, being it the physics, biology or chemistry. The first SAS will also set the criteria for future monitoring, with regard to both resolution and parameters. The ultimate vision is a survey repeated at approximately decadal intervals and that, having established the baseline with the SAS effort, change in key ecosystem, carbon cycling and biogeochemical characteristics and their physical foundations would be detected through comparison.

The involvement and planning of ice going research vessels from several nations will set a new standard for international cooperation in the Arctic, and coordination of logistics as well as research procedures. These include methods applied, technical development, and training of next generation polar scientists. We foresee that the SAS endeavor will form an exceptional long-term legacy for future scientists and stakeholders.

Scientific Scope

The Synoptic Arctic Survey effort focuses on a single, overarching question on a Pan-Arctic scale:

What are the present state and major ongoing transformations of the Arctic marine system?

We seek to describe the present state of the AO and to provide the foundation against which future states can by compared to quantify change. The Synoptic Arctic Survey will pursue three key foci:

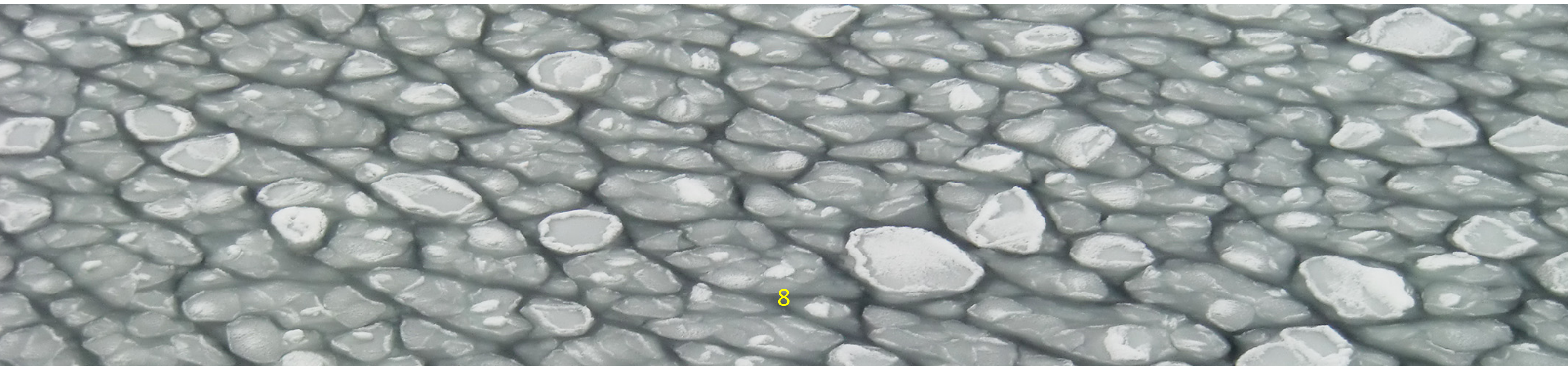
1) Physical drivers of importance to the ecosystem and carbon cycle,
2) Ecosystem response and
3) Carbon cycle and ocean acidification

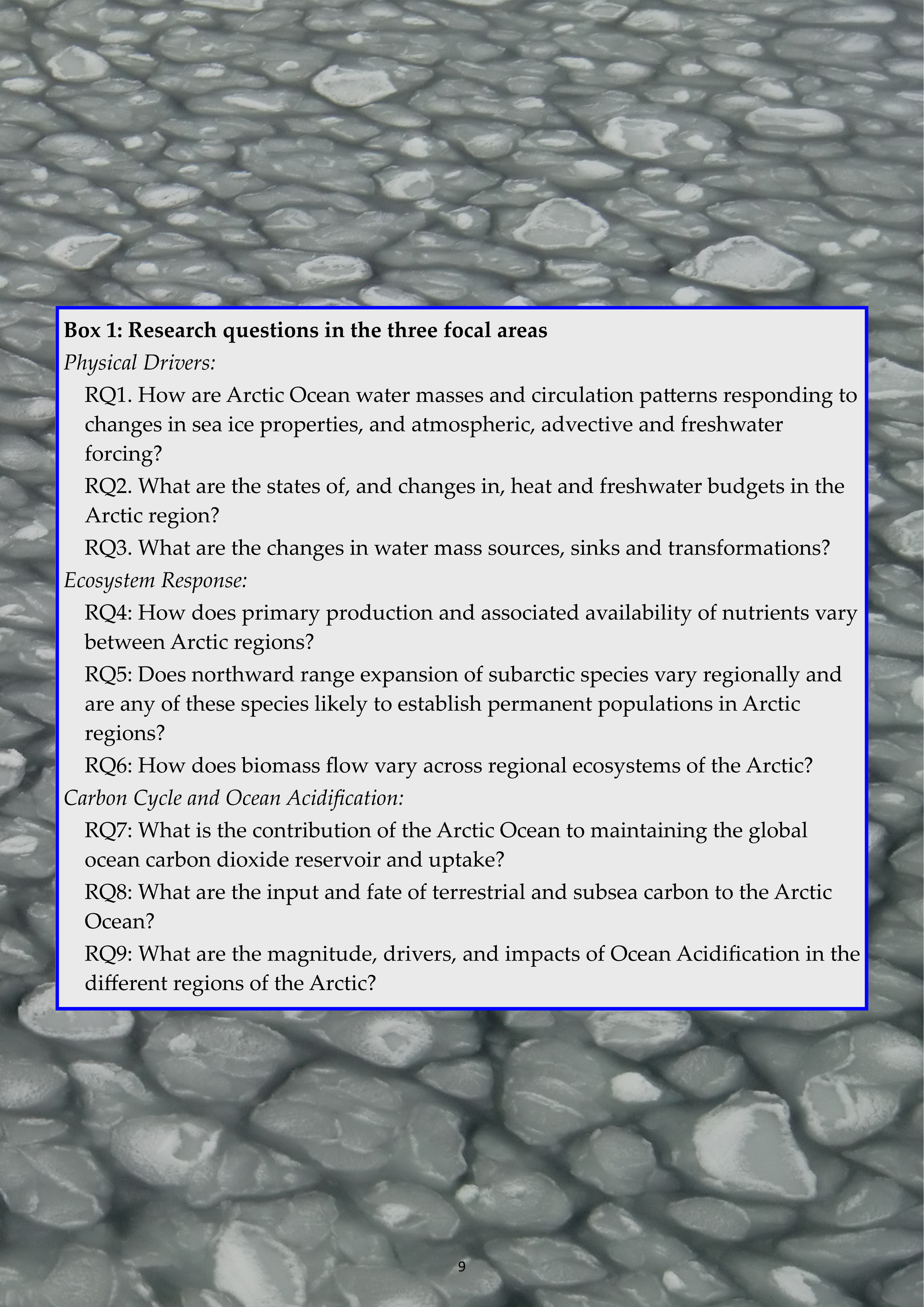
Each focal area has three specific questions (Box 1) that are key to understanding ongoing transformations in the system, but that cannot at present be completely answered because of lack of a baseline or foundational understanding at pan-Arctic and synoptic scales (Fig. 3). Because physical oceanography is the fundamental structure underlying biological and chemical characteristics and has a longer record for observing, understanding and availability data are more mature for physical than for ecosystem and carbon Arctic marine sciences. This permits inquiry in the physical oceanography focal area to target quantification of change while inquiries in the ecosystem and carbon cycle focal areas are targeted more at basic understanding and establishment of a baseline that will permit change detection at a Pan-Arctic scale moving forward from the SAS expedition.

The SAS seeks to achieve near-synoptic sampling at a Pan-Arctic scale with full depth hydrographic sections, encompassing as many different regions and gateways as possible with the assets and resources available. Some of the suggested sections cover regions that have only rarely or never been characterized, while others cover the regions that have been more frequently sampled. Further, the SAS is envisioned to take place during the summer months, not only because the AO is most accessible in this season but also since most previous work has been conducted during those periods for comparative purposes. Altogether this spatial and temporal sampling strategy enables detection of change for those characteristics and regions where previous information is available, in addition to providing the required comprehensive characterization of today's AO in terms of physics, ecosystems and carbon.

The SAS team recognizes that great deficiencies exist in our understanding of the ecosystem and carbon cycle for periods of the year outside of the summer season and that seasonality and the spring bloom period are critical times for both focal areas. To achieve full single year spatial coverage of the AO, multiple ships will be required to sample the major provinces of the Pan-Arctic system and the key gateways. Given that effort, it is not realistic to expand the sampling to encompass the full range of seasonality and simultaneously retain Pan-Arctic synopticity. Some measurements can be augmented spatially and temporally through the use of autonomous assets (e.g., moorings, ice tethered profilers, satellites, AUVs, see section *Adjoint Observations and Activities*) and collaborations will be sought, while other measurements still cannot be obtained using autonomous platforms and existing sensors. To some extent, modeling can expand understanding through the annual cycle, although deficiencies in our baseline understanding of ecosystem processes and carbon cycling hamper our ability to develop realistic and accurate models as well. Nonetheless, modeling is an important tool that can be used together with empirical efforts and foresee that there will be considerable progress made through the Year of Polar Prediction (YOPP, lasting until 2023) which seeks to advance environmental prediction capabilities for the polar regions. Greater temporal understanding also can be gained through synergies and collaborations with other international programs such as The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) and the Distributed Biological Observatory (DBO) efforts.

Methodologies, national and international level organizations, and data policies will draw upon ongoing programs such as MOSAiC, DBO, GO-SHIP (Global Ocean Ship-Based Hydrography Investigations Program), PAG (Pacific Arctic Group), GEOTRACES (an international programme that improve our understanding of biogeochemical cycles and large-scale distribution of trace elements and their isotopes in the marine environment, see also recent Arctic GEOTRACES), and the CAFF Arctic Marine Biodiversity Monitoring Plan [*Gill et al*., 2011]. Collaborations with these and other programs, and individual efforts will actively be sought.





Box 1: Research questions in the three focal areas

Physical Drivers:

RQ1. How are Arctic Ocean water masses and circulation patterns responding to changes in sea ice properties, and atmospheric, advective and freshwater forcing?

RQ2. What are the states of, and changes in, heat and freshwater budgets in the Arctic region?

RQ3. What are the changes in water mass sources, sinks and transformations?

Ecosystem Response:

RQ4: How does primary production and associated availability of nutrients vary between Arctic regions?

RQ5: Does northward range expansion of subarctic species vary regionally and are any of these species likely to establish permanent populations in Arctic regions?

RQ6: How does biomass flow vary across regional ecosystems of the Arctic?

Carbon Cycle and Ocean Acidification:

RQ7: What is the contribution of the Arctic Ocean to maintaining the global ocean carbon dioxide reservoir and uptake?

RQ8: What are the input and fate of terrestrial and subsea carbon to the Arctic Ocean?

RQ9: What are the magnitude, drivers, and impacts of Ocean Acidification in the different regions of the Arctic?

SCIENCE QUESTIONS AND GOALS

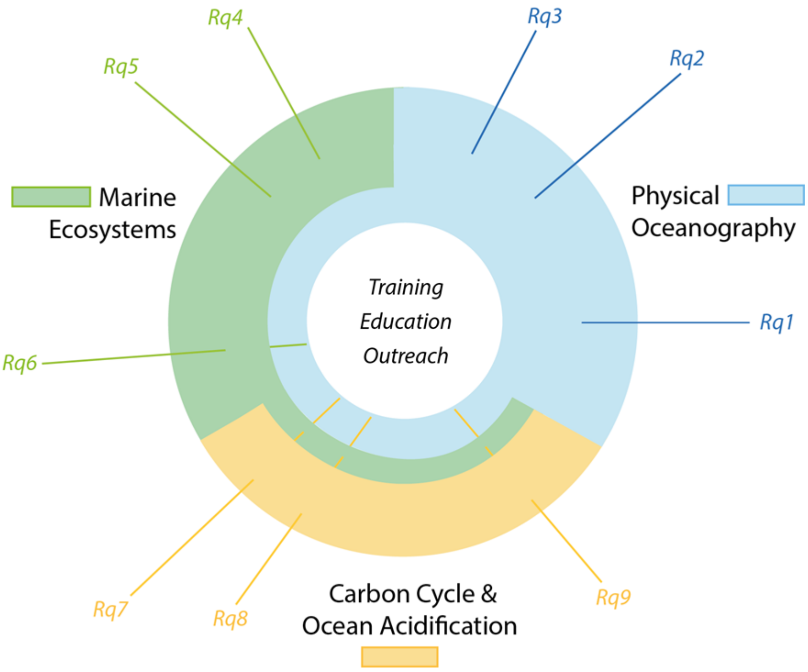


Figure 3. SAS consists of three major foci (1) Physical Drivers (in blue), (2) Ecosystem Response (green), and (3) Carbon Cycle and Acidification (yellow). Each focus area is broken down into three research questions (RQ) which to various degrees requires understanding from all three foci.

PHYSICAL DRIVERS

Background

The AO is a major player in the global oceanic circulation system being both a direct link for surface water from the Pacific to the Atlantic Ocean and a contributor to the formation of deep water that constitutes the northern limb of the Atlantic Meridional Overturning Circulation (AMOC). Climate change is manifested by decreasing sea ice coverage and volume, as well as by increasing temperatures of the inflowing Atlantic water. A potential coupling between the Atlantic inflow and sea ice loss in the Eurasian Basin has been suggested [*Polyakov et al., 2017*].

Changes in the AO feed back to the global climate system through not only ocean circulation itself but also by the effect of that circulation on the large scale atmospheric flow pattern. It has, for instance, been suggested that if the Arctic continues to warm in response to increasing greenhouse-gas concentrations, the frequency of extreme weather events caused by persistent jet-stream patterns will increase [*Francis and Vavrus, 2015*]. There are further indications that the extreme cold weather during some recent winters in the US East Coasts is connected to the warming of the Arctic [*Overland et al., 2015; 2016*].

The poleward transport of heat in the Atlantic Ocean is largely accomplished by the AMOC, which varies in strength on annual to multi-decadal time scales, with subsequent impacts on the large-scale climate and marine ecosystems, including the sequestration of anthropogenic carbon dioxide (CO$_2$, *see Carbon Cycle section*). Model simulations where the AMOC is forcibly stopped by experimenters indicate a subsequent widespread cooling throughout the Northern Hemisphere, in particular Northwestern Europe [*Jackson et al.*, 2015]. While model simulation indicates a weakening of the AMOC, long-time series documenting the exchange flow across the Greenland-Scotland Ridge show no such decline [*Hansen et al.,* 2015]. This emphasizes the need for observations in order to examine changes of ocean climate as well as to better understand the processes behind such changes.

Fundamental to the understanding of the AO, including the ecosystem and carbon cycle, is the distribution of water masses and their circulation. The AO water column can be considered as a stacking of mostly non-interacting layers, and categorized into typical western AO (Amerasian Basin) or eastern AO (Eurasian Basin) profiles [*McLaughlin et al.,* 1996]. In regions of ice cover the water column typically has a thin, ~5-10 m thick, polar mixed layer, but in ice-free regions wind-driven mixed layers may be more than twice as deep [*Rainville et al.,* 2011], up to 25–50 m. Large expanses of the upper ~150 m, especially in the Amerasian sector, are dominated by Pacific waters entering via Bering Strait.

Waters from the Atlantic Ocean account for the preponderance of the Arctic Ocean's volume [*Macdonald et al.,* 2004], but the term “Atlantic Layer” is reserved for a relatively warm subsurface layer distinguished by its temperature maximum near 0.5-1.5 °C around 200-400 m.

The Atlantic Layer is separated from the polar mixed layer by a cold halocline [*Aagaard et al.*, 1981; *Rudels et al.*, 1996] - which is formed by either brine-rejection-driven convection topped off with fresher cold waters (convective halocline), or injection of cold salty shelf waters (advective halocline) [*Steele and Boyd*, 1998].

Below the Atlantic Layer, the deep waters are colder and saltier and are slightly warmer and saltier in the western AO than in the eastern AO. The bottom layers are remarkably homogenous, often more than 1000 m thick, weakly ventilated and contain thermohaline staircases implying geothermal heating from below [*Timmermans et al.*, 2003].

Waters of Atlantic origin constitute a substantial reservoir of subsurface heat, and as mentioned provide a "climate handshake" between the AO and the rest of the world ocean. The flow of Atlantic water occurs as a pan-Arctic boundary current system, often termed the Arctic Circumpolar Boundary Current [*Pnyushkov et al.*, 2015; *Woodgate et al.*, 2001; *Rudels et al.*, 1999]. The boundary current follows topographic slopes cyclonically around the basins and along the ocean ridges, with the core of the current lying between the ~500 - 3000 m isobaths (see Fig. 4).

The prevailing view is that the bulk of the Pacific waters travel northward from the Bering Strait and exit the shelf via Herald Canyon and Herald Valley and through Barrow Canyon in the east, turning to the east along the Beaufort Shelf. Pacific waters are found primarily on the Canada Basin side of the Mendeleev Ridge, and episodically also in the Makarov Basin, in both basins to near the Lomonosov Ridge [*McLaughlin et al.*, 1996; *Swift et al.*, 2005]. The annual extent of Pacific water is likely related to the position of the Transpolar Drift of sea ice [*Rigor et al.*, 2004] and the Arctic Oscillation [*Thompson and Wallace*, 1998]. Pacific waters exit the AO via the Fram Strait and the Canadian Archipelago, their high nutrients fueling ecosystems in the polynyas of the Archipelago [*Tremblay et al.*, 2002]. The AO deep waters, both from the Amerasian Basin and from the Eurasian Basin, exit through Fram Strait and contribute to the deeper layers in the Nordic Seas. Schematic illustrations of the circulation in various layers are provided in Fig. 4.

The availability of data describing the physical oceanography of the AO to date has been sufficient to determine the overall water mass properties and circulation patterns over the past few decades. Evidence of both natural variations and anthropogenically forced change is now emerging (see section *A new Arctic Ocean*). Three research questions regarding their causes, nature and impacts have been formulated. The SAS can significantly contribute to their resolution, in particular when combined with available historical data and results from more process oriented activities in the AO such as the recent N-ICE [Norwegian Young Sea Ice Cruise, e.g., *Koenig et al.*, 2016; *Meyer et al.*, 2017; *Peterson et al.*, 2017] and the upcoming MOSAiC. Further, the physical oceanographic data and insight are essential for the ecosystem and carbon work of the SAS.

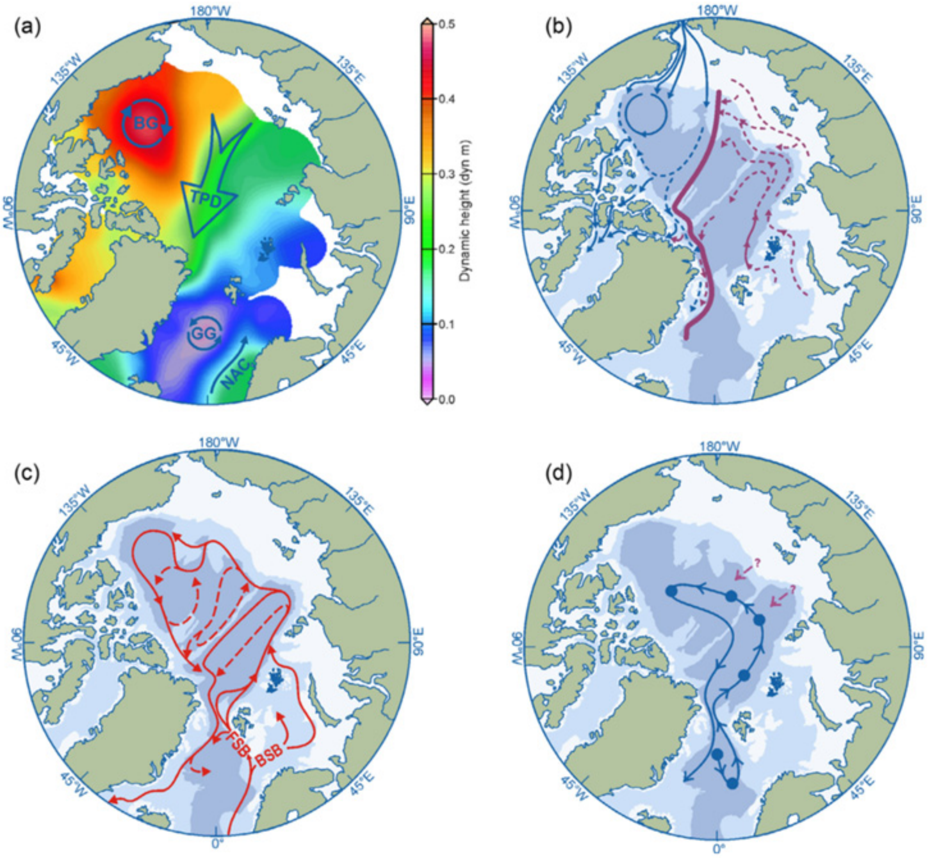


Figure 4. Schematic representations of Arctic Ocean circulation: (a) Surface circulation of the Arctic Ocean as shown by dynamic topography (20/400 dbar) (World Ocean Database 2013), (b) summary of mid-water halocline sources, flows and associated fronts (blue shows Pacific-origin waters, maroon shows Atlantic-origin waters, thick maroon line depicts the front between them) after *McLaughlin et al.* [1996]; (c) schematic representation of the Arctic Circumpolar Boundary Current system derived from Atlantic water inflows [after *Aksenov et al.*, 2011; *Rudels et al.*, 2013]; and (d) schematic representation of deep water exchange [*Aagaard et al.*, 1985]. BG is the Beaufort Gyre, BSB is the Barents Sea Branch, FSB is the Fram Strait Branch, GG is the Greenland Gyre, NAC is the Norwegian-Atlantic Current, NCC is the Norwegian Coastal Current, TPD is the Transpolar Drift. [Figure copied from *Blum et al.*, 2015.]

Research questions:

RQ1. How are Arctic Ocean water masses and circulation patterns responding to changes in sea ice properties, and atmospheric, advective and freshwater forcing?

RQ2. What are the states of, and changes in, heat and freshwater budgets in the Arctic region?

RQ3. What are the changes in water mass sources, sinks and transformations?

RQ1. How are Arctic Ocean water masses and circulation patterns responding to changes in sea ice properties, and atmospheric, advective and freshwater forcing?

Distribution and circulation of water masses are determined by several factors like the earth rotation, atmospheric pressure field and vertical density field. The two latter are now subjected to anthropogenic forcing, with consequences for the distribution and circulation of Arctic Ocean water masses

Rationale

Two defining features of the AO are its perennial sea-ice cover and its permanently stratified halocline complex, both of which shield the warm underling Atlantic source waters from the atmosphere. Historically, perennial sea ice covered about half the AO [*Stroeve et al.*, 2007], but in recent decades it has been strongly reduced in both extent [*Serreze and Stroeve*, 2015] and thickness [*Kwok and Cunningham*, 2015]. The sea ice, seasonally covering the entire AO, is the key to the remarkable physical quietness of the AO; sea ice modifies the transfer of wind momentum to the water and suppresses the generation of surface and internal waves. As sea ice thins and retreats, however, the role of the underling ocean becomes increasingly important [*Carmack et al.*, 2015]. Already a change in ocean structure have been noted, with halocline stratification decreasing in the Nansen Basin [*Polyakov et al.*, 2018] and increasing in the Canada Basin [*McLaughlin et al.*, 2011], and widespread changes in the temperatures of Atlantic source waters [*Polyakov et al.*, 2011].

If brought to the surface, the Atlantic water layer contains sufficient heat to almost instantly melt the AO sea-ice cover. However, the low level of subsurface energy allows vertical mixing to be dominated by double diffusive convection [*Polyakov et al., 2012*] and by laterally interleaving, double diffusive layers perpendicular to the mean flow [e.g., *Carmack et al.*, 1998; *Woodgate et al.*, 2007; *McLaughlin et al.*, 2009]. Consequently the reduction in sea-ice cover will have a profound impact on the mixing processes forming the AO water column both through changes to the water mass transformations related to the ice-freezing and melting processes [Polyakov et al., 2013], and through changes in the efficiency of wind-induced mixing.

The present understanding is based on observations collected over several decades when the atmospheric pressure field has varied substantially. Consequently, no time-fixed point of the state of the AO yet exists. Changing weather patterns, influenced by enhanced vertical heat fluxes from larger areas of open water, will affect the barotropic forcing of ocean circulation. At the same time, changes in the sea-ice cover, freshwater sources, and advected subarctic water masses will impose changes to the baroclinic circulation through shifts in water mass transformation and distribution.

While past observations provide a general understanding of Arctic Ocean water masses and their circulation, much is lacking in the critical details required to understand, manage and model the system in the broader context of global change. A comprehensive picture of water mass structure is a necessary backdrop for evaluating key physical processes and their role in Arctic change. For example, the front separating the weakly stratified halocline complex of the Eurasian Basin from that of the strongly stratified Amerasian Basin has been observed to shift [*McLaughlin et al.*, 1996], but its exact position cannot be determined by a transect from single ship, SAS will deal with this. Similar arguments hold for the front created by river runoff from the Siberian shelf seas towards Fram Strait [*Anderson et al.*, 2004]. Further, the extent and vertical structure of the Beaufort Gyre is highly variable over sub-decadal time scales, but this is only known because of a repeat grid of stations carried out annually in the southern Canada Basin since 2003 [*Proshutinsky et al., 2009*]. Likewise, changes in stratification along the Siberian slope are only known because of a repeat grid of hydrographic stations [*Polyakov et al.*, 2017]. While both of these programs show the crucial value importance of three-dimensional, synoptic mapping, they currently cover a limited area, and cannot resolve the full Arctic marine system. Obtaining an anchor point to record the present state of the AO with respect to these factors will prove invaluable when assessing the rate of ongoing changes and will enhance our understanding of the Arctic climate system and its subsequent role on the global system.

How will this be answered?

SAS will provide the three-dimensional view of AO structure. Specifically, SAS will provide the temperature, salinity and tracer properties (e.g., dissolved oxygen, nutrient, stable isotope, trace element and carbon system data) to quantitatively define water mass distributions, their frontal boundaries both horizontally and vertically, and the pathways of spreading that define their structures and residence times. Together with mooring data from collaborative programs an assessment of seasonality will also emerge. To determine changes in AO water masses and circulation, the SAS data will be compared with historical data (e.g., as available in GLODAP [*Olsen et al.*, 2016] and UDASH [*Behrendt et al.*, 2018]). These changes will be interpreted in light of known changes in sea ice, atmospheric circulation and advected forcings from the well monitored subarctic regions. SAS will further provide the benchmark for assessment of future change.

RQ2. What are the states of, and changes in, heat and freshwater budgets in the Arctic region?

The stratification of the AO is mainly determined by the salinity, with the upper waters strongly impacted by sea ice melt, river runoff and the inflow of Pacific-origin waters. Halocline structure and strength varies greatly across the breadth of the AO, and multiple mechanisms for the formation of water masses comprising the halocline complex exist [e.g., *Carmack et al.*, 2008]. Sea ice can melt by heat from both the underlying waters as well as from atmospheric radiation and heating, and in ice free waters the temperature can increase substantially, with impacts on the ecosystem and carbon cycle.

Rationale

A principal component of the AO heat budget is the inflow of warm Atlantic water. In the Fram Strait the total northward flow is about 7 Sv [*Fahrbach et al.*, 2001], but complex recirculation elements in the strait return approximately half of that to the south [*Rudels et al.*, 2000]. The bulk of the remaining heat, ~35 TW, in the West Spitsbergen Current is transported northward [*Walczowski*, 2015]. A substantial amount of that heat drives melting of sea ice in the region north of Svalbard, decreasing the temperature to the freezing point in the upper ~100 m [*Rudels et al.*, 1996]. The Barents Sea inflow is around 2 Sv on average but with a significant seasonal variability [*Ingvaldsen et al.*, 2004], transporting around 70 TW of heat [*Smedsrud et al.*, 2013]. However, the Atlantic water is substantially modified during transit through the Barents Sea and consequently its heat transport to the deep basins of the AO is negligible [*Gammelsrød et al.*, 2009]. About 0.8 Sv of water enters the AO through the Bering Strait [*Roach et al.*, 1995], with significant seasonal variations, from about 0.4 Sv in winter to about 1.2 Sv in summer [*Woodgate et al.*, 2005, *Woodgate*, 2018]. The associated heat transport is ~15 TW on average. In total, approximately 120 TW of oceanic heat enters the AO, but about half is lost to the atmosphere within the Barents Sea. All these estimates are approximate, with uncertainties typically about 25%.

The heat transport to the AO varies on timescales from days to decades, related to changes in both volume, and in the longer term more importantly, in temperature. Recent decades have seen an increase in the heat transport arising from increased temperature of the inflowing Atlantic water [e.g., *Polyakov et al.*, 2017].

Within the AO almost all physical, biological, and biogeochemical processes are influenced by the local quantities and qualities of the freshwater. Freshwater is supplied to the AO through moisture flux convergence above the ocean (~0.06 Sv), drainage from adjacent basins (~0.1 Sv), and as low-salinity water entering from the Pacific Ocean [*Aagaard and Carmack*, 1989; *Serreze et al.*, 2006]. Future conditions under warming scenarios are likely to include increased runoff as well as increased inputs from glacial melt and permafrost. Changes in the phenology of discharge are also almost certain to occur.

Sea ice will likely continue to form in winter, but model results indicate its thickness will diminish further under scenarios of increased global warming. It is therefore feasible that the area of seasonal ice may increase while its thickness will decrease: the volume of freshwater involved in the annual freeze-melt cycle, ignoring for now the advected components, is the product of the two. Hence, the seasonal dynamics of the sea ice distribution strongly impact the freshwater budget [*Haine et al.*, 2015].

Observed changes with the increase in freshwater storage during the 2000s include faster circulation, altered water mass distributions, increased surface heat content, increased sea level along the Siberian coast, decreased nutrient supply, changed algal communities toward smaller cell sizes, and enhanced ocean acidification [e.g., *Bluhm et al.*, 2015].

How will this be answered?

Both heat and freshwater budgets (source, disposition, storage and export) in the AO are strongly constrained by advective inputs from the neighboring subarctic Atlantic and Pacific across the main gateways: Fram Strait, the Barents Sea, Bering Strait and Davis Strait. These will be constrained using the SAS data across each of these gateways, refining previous estimates from collaborative projects based on current meter moorings (e.g., Hausgarten) and/or inverse analyses [e.g., *Tsubouchi et al.*, 2012]. SAS will also carry out transects crossing the shelf and slope to identify heat and freshwater spreading pathways and storage within the four main basins and will identify water mass boundaries. All of this will provide a benchmark to track future changes in both heat and freshwater storage that follow frontal reorganization associated with changes in atmospheric forcing.

RQ3. What are the changes in water mass sources, sinks and transformations?

The AO is one of the drivers of the AMOC and as such also contributes to the oceanic sequestration of anthropogenic CO_2. The ventilation does not contribute much to the deepest waters, thus keeping their conditions quite stable. Changes in these conditions might feedback substantially to climate.

Rationale

Changes in the quantity or properties of the inflowing source waters, the freshwater input through precipitation or river runoff, and the formation of sea ice will affect subsequent water mass transformations and eventually sinks, leading to potential dynamical shifts in the AO.

The ongoing reduction in sea-ice cover affects water mass transformations directly through changes in the amount of brine release and in the geographical locations where brine release occurs, and indirectly through changes to the wind-induced vertical mixing in the upper layer of the AO. Furthermore, the changing sea-ice distribution affects ocean-to-air heat fluxes and subsequently the atmospheric circulation that governs the barotropic advection to and within the AO. While these changes call for extensive process studies, an anchor point in time representing the present state in the AO will be vital to determine the rate of change.

The Kara, Laptev, East Siberian and Beaufort Seas are interior shelf seas of the Arctic Mediterranean and are distinguished from inflow and outflow shelves (the Barents Sea and the Chukchi Sea) by their principal forcing dynamics [*Carmack and Wassman*, 2006]. Along their southern (continental) boundary the interior shelves are dominated by the major rivers flowing into the Arctic. In the mid-shelf region, wind and ice motion surface stresses dominate mixing and circulation, resulting in high variability. Along the outer shelf, wind-forced upwelling events drive shelf-basin exchange that pushes river plumes offshore [*Macdonald et al.*, 1999] and draws nutrient-rich halocline waters onto the shelf [*Carmack and Chapman*, 2003; *Williams and Carmack*, 2015]. Shelf-basin exchange is further modified by shelf-break morphometry (e.g., canyons, valleys, headlands and bottom slope) [*Williams et al.*, 2008]. Brine formation from sea ice production contributes to high salinity bottom water on the shallow shelves [e.g,. *Aagaard et al.*, 1981; *Anderson et al.*, 1988] into which nutrients are released from the sediment surface by mineralization of organic matter [e.g,. *Anderson et al.*, 2011]. These nutrient rich waters flow off the shelf and act as a source for halocline waters and also contribute to the transformation of deeper water masses [e.g., *Anderson et al.*, 2017].

The numerous deep stations occupied in the AO during the last 20 years combined with the high accuracy of the measurements has revealed subtle differences between the deep and bottom waters in the separate basins, more than the obvious higher temperatures and salinities in the Amerasian Basin relative to the Eurasian Basin. Exchange of water across the Lomonosov Ridge has been a topic of discussion during the last decades. *Rudels* [2012] suggested that the exchanges were dependent upon the pressure gradient at sill depth. In 2005 the water column above 2000 m was less dense in the Amundsen Basin compared to the Makarov Basin and the negative pressure gradient at 2000 m would be directed from the Makarov to the Amundsen Basin [*Björk et al.*, 2007]. In 1996, when *R/V Polarstern* crossed the Lomonosov Ridge, the water column in the Amundsen Basin was denser than that in the Makarov Basin [*Rudels*, 2012]. Moreover, the source for deep water in the Makarov Basin, which lacks a deep temperature minimum, is still under debate.

How will this be answered?

The synoptic data collected in SAS will remove the aliasing influence of seasonality and interannual variability and enable better detection of regional differences and decadal changes in water mass sources, sinks and transformations. In particular SAS will carry out transects crossing the shelf and slope to identify transformations of Atlantic and Pacific origin waters on shelves prior to entering the basins. SAS will thus generate a synchronous data set that will contribute to an accurate assessment of regionality in these changes. SAS will also provide information required for model development and parameterization. SAS data will expand understanding of shelf-basin interactions, including processes of brine drainage [*Aagaard et al., 1981*] and shelf-break upwelling [*Williams and Carmack*, 2015]. Changes in the inflow and spreading of waters from both the Pacific and Atlantic Oceans will also be quantified.

ECOSYSTEM RESPONSE

Background

The structure of an AO ecosystem can be viewed as relatively simple, with species and trophic linkages common to many regions of this ocean and physical drivers that are susceptible to ongoing environmental change. Important physical drivers include advection, from outside of the Arctic and between regions, the extent, age, snow cover, and timing of sea ice, and ocean temperature.

The link to sea ice is particularly important, with changing seasonality of sea ice potentially impacting the timing and magnitude of primary and secondary production with possible negative impacts on current key species. Rapid sea ice retreat and seawater warming is particularly acute on the inflow shelves influenced by exchange with the Pacific and Atlantic Oceans [*Kedra et al.*, 2015]. For example, northern regions of the Pacific Arctic shelf seas and deeper into the Arctic Basin are experiencing earlier and more extensive sea ice retreat, atmospheric changes, and northward advection of warming Pacific water into the region.

Regional differences in sea ice cover may also represent different stages in the evolution of the Arctic system, from perennially to seasonally sea ice covered, so that regional comparisons of trophic structure, linkages and carbon cycling can yield greater understanding of the future impacts of further environmental changes. For example, the Chukchi and Barents Seas are located at similar latitudes yet have very different ecosystem structures. The Chukchi Sea has a rich and abundant benthic community that receives much of the primary production, leaving low abundances of consumers in the water column and few pelagic fish (a benthically dominated ecosystem). By contrast, the Barents Sea has abundant zooplankton and a vigorous pelagic fish community that supports important commercial fisheries, with a relatively reduced benthic biomass (a pelagically dominated ecosystem). Much of the ecosystem structure and functioning of these two marginal seas can be inferred from quantification of these key standing stocks, although many measurements also have been made of carbon transformations between ecosystem components. Similar understanding of other regional differences, particularly for the central AO and more remote marginal seas, is lacking.

Primary production, at the base of the food chain, takes place both by phytoplankton and by sea ice algae and is regulated by a complex interplay of light, nutrient availability, and water column stability [reviewed in *Tremblay et al.*, 2015]. Light availability to the underside of the sea ice or to the water column is controlled by the annual light cycle, the presence of sea ice, and the depth of snow on the surface of the sea ice. Cloudiness also can significantly limit light availability [*Bélanger et al.*, 2013] and in turn primary production. A subsurface chlorophyll maximum also is frequently observed [*Tremblay et al.*, 2015]. Nutrient supply to the upper water column depends on annual regeneration, stratification and vertical mixing of nutrients from depth, and lateral input of nutrients through advection from outside of the central AO [e.g., *Codispoti et al.*, 2013; *Hill et al.*, 2013]. Water column stability limits the upward mixing of nutrients from below the pycnocline; increased storminess under climate change could eventually breach the pycnocline to release these nutrients for use in primary production. Similarly, to lower latitudes, the size composition of phytoplankton shifts seasonally from large diatoms in the spring to smaller flagellates during the summer, with a fall diatom bloom occurring in some marginal seas [e.g., *Smith and Shakshaug*, 1990; *Nelson et al.*, 2014].

While traditionally the AO was thought to be dominated by large phytoplankton cells, our recent understanding suggests that microbes and small eukaryotic organisms are abundant and responsible for much of the carbon cycling and food web base over continental shelves and in the Arctic Basin [*Sherr et al*., 2003; *Lovejoy et al*., 2006; *Li et al*., 2013]. The diversity of the small size components (bacteria to microzoopankton and benthic meiofauna) is extremely difficult or impossible to capture with traditional morphological techniques, but next generation sequencing is offering a feasible approach to understand their populations and role in carbon cycling [e.g., *Lovejoy and Potvin*, 2011; *Bowman et al*., 2012, 2015].

Some microbial roles in carbon cycling, previously thought to be less important in the AO than at lower latitudes, are emerging as potentially critical, especially in sea ice and when linked to nitrogen cycling [e.g., primary production through bacterial nitrification; *Fripiat et al*., 2014; *Firth et al*., 2016]. The importance of microzooplankton to planktonic carbon pathways has been increasingly recognized [e.g., *Sherr et al*., 1997, 2003]. Microzooplankton are recognized as significant consumers of primary producers during summer, when phytoplankton cells are small, and are important prey for mesozooplankton [*Campbell et al*., 2009; *Sherr et al*., 2009].

Mesozooplankton biomass in the central AO is dominated at most locations and depths by the large copepod *Calanus hyperboreus*, with lesser contributions (> 5% of biomass) by the copepods *C. glacialis*, *Microcalanus* spp., *Metridia longa*, and *Paraeuchaeta glacialis* and the chaetognaths, based on representative data from the Canada Basin [*Kosobokova and Hopcroft*, 2010]. Small copepods dominate numerically, including *M. pygmaeus*, *Oithona similis*, and *Oncaea* spp. [e.g., *Ashjian et al*., 2003].

In the eastern AO, the subarctic species *C. finmarchicus* also is a significant component of the biomass [e.g., *Hirche and Kosobokova*, 2007]. Considerable attention has been devoted to the ecology of *C. glacialis* and *C. hyperboreus*. Although present throughout the central AO, *C. glacialis* is considered to be more abundant in the marginal shelf and slope regions while *C. hyperboreus* is more important in the basins [*Falk-Petersen et al*., 2007]. The species follow multiple year life histories, migrating to depth to overwinter, subsisting on stored lipid, and returning to the surface during the productive season to feed. Currently, their life cycles are well matched to the phenology of sea ice and snow, with reproduction timed so that the appearance of first feeding young coincides with the timing of primary production by sea ice algae or phytoplankton. Both *Calanus* spp. are important prey for Arctic cod, which in turn are prey for seals, beluga whales, and seabirds.

Benthic communities in western (Chukchi, Beaufort) and eastern (Barents, Laptev) Arctic shelf seas are fairly well described. The Chukchi Sea is characterized by extremely high benthic biomass [*Grebmeier et al*., 2015] while the Beaufort, Laptev, and Barents are of much lower biomass [*Dunton et al*., 2005; *Denisenko et al*., 2015]. There are only a few studies on high Arctic benthic food webs [reviewed by *Bluhm et al*., 2015; *Kedra et al*., 2015]. These show that the benthic biomass is very low compared to the shelf systems [*Bluhm and Grebmeier*, 2011].

Fishes are important trophic connectors between planktonic and benthic invertebrates and higher trophic levels [*Bluhm and Gradinger*, 2008] and need monitoring for the potential of a future Arctic fishery [*NPFMC*, 2009]. Arctic fisheries and ecosystem studies in the Central AO are topics for a developing international agreement for an integrated ecosystem assessment for the High Arctic. Seabirds and marine mammals are also consumers on slope and into the Arctic basin [*Moore et al*., 2014], emphasizing the need to track upper trophic organisms as well as their prey base.

Three questions have been identified that are particularly timely and significant to the future structure of AO ecosystem. Some aspects of the questions can be addressed through the envisioned first SAS expedition; other aspects will require information from that expedition as baseline against which future work can be compared. The questions are intricately associated with physical oceanography, a key driver of much of the ecosystem structure and functioning, and with the cycling of carbon, as biological processes are key to many carbon transformations. The questions are also relevant to the overarching societal challenges faced in the Arctic on both local and global scales.

Research questions:

RQ4: How does primary production and associated availability of nutrients vary between Arctic regions?

RQ5: Does northward range expansion of subarctic species vary regionally and are any of these species likely to establish permanent populations in Arctic regions?

RQ6: How does biomass flow vary across regional ecosystems of the Arctic?

RQ4: How does primary production and associated availability of nutrients vary between Arctic regions?

The reduction of seasonal sea ice cover in the AO immediately suggests that with more light will come more primary production. Yet in reality, the primary production responses to these cryosphere changes are complicated, depending also on the availability of nutrients and the stability of the water column.

Rationale

Productivity and ice algal and phytoplankton abundance measurements remain sparse for the central AO, particularly in recent years that have seen the demise of central AO expeditions and ice islands, as demonstrated in recent syntheses of available pan-Arctic chlorophyll and primary production data and of the annual evolution of ice algal production [*Codispoti et al.*, 2013; *Hill et al.*, 2013; *Matrai et al.*, 2013; *Leu et al.*, 2015]. Early work, based from ice islands or in the Archipelago, suggested that the central AO was of very low productivity [e.g., *English*, 1961]. During the 1994 Trans-Arctic section, higher levels of primary production were observed than previously believed to be occurring in the central AO [e.g., *Wheeler et al.*, 1996; *Gosselin et al.*, 1997] and transformed the perception of the central AO as a biological desert to one that supports relatively high production. In addition, ice algal primary production was observed to be a significant component of the total annual primary production [*Gosselin et al.*, 1997]. It is not clear if the greater levels of primary production represent an actual change or greater resolution due to improved access and methodology [*Pomeroy*, 1997]. Since these efforts, work in marginal seas has substantiated the perception of the AO as being of greater productivity than the desert to which it was previously ascribed. The importance of subsurface chlorophyll maxima to primary productivity also is poorly quantified [*Trembley et al.*, 2015, *Hill et al.*, 2018].

Under ongoing climate change, modifications to the physical environment could change the phenology of primary production by ice algae and phytoplankton in response to changes in the timing of the formation and retreat of sea ice and snow cover or could increase the magnitude of primary production through increases in nutrient supply to the central AO [e.g., *Tremblay et al.*, 2015; *Frey et al.*, 2017]. It also has been hypothesized that increased melt pond porosity and lead formation under climate change could support more frequent massive under-ice blooms such as observed in the Chukchi Sea in 2012 and 2013 [*Arrigo et al.*, 2012] and in the AO in 2015 [*Assmy et al.*, 2017]. The seasonal opening of ice-covered areas drives primary production through increased solar radiation and light penetration in surface waters, particularly in the marginal ice zone, with limitations of this production by stratification and nutrient availability that vary regionally [*Popova et al.*, 2012; *Grebmeier et al.*, 2015; *Tremblay et al.*, 2015]. Since the environmental drivers vary between AO regions there should be corresponding regional differences in the primary production response. The questions of how the primary producers may respond to changing physical environments and whether there will be greater nutrient availability and thus standing stocks of phytoplankton have important consequences to a range of key parameters, including export carbon flux and the biomass of secondary producers and upper trophic level organisms (e.g., fish) that can be supported in the AO.

A few efforts have suggested that changes in the phytoplankton community and in primary productivity are ongoing. *Li et al.* [2009] showed increasing chlorophyll standing stocks and a shift from larger to smaller cells concomitant with ocean warming in the Beaufort Sea over five consecutive years, although a longer time record indicated that the trend was not robust [*Li et al.*, 2013]. Overall, most studies have concentrated on bulk measures of phytoplankton abundance (chlorophyll) rather than on species composition, with some exceptions [*Sergeeva et al.*, 2009, *Crawford et al.*, 2018]. Analyses of ocean color from satellites have suggested that primary production in the surface waters has increased over recent years [*Arrigo and van Djiken*, 2011, 2015; *Bélanger et al.*, 2013] in association with decreasing sea ice cover [*Kahru et al.*, 2016]. Satellite data are limited, however, because they cannot resolve the pervasive deep chlorophyll layer that is characteristic of the Arctic seas and basins [*Tremblay et al.*, 2015; *Frey et al.*, 2017].

Changes in primary production and carbon cycling could impact the availability of fish or other commercial and subsistence resources in the AO. Changes in primary production could also modify the uptake or release of CO_2 from surface waters that would feedback to CO_2-driven climate warming.

Although multiple lines of evidence indicate that light availability is increasing in the central AO, changes in nutrient availability are far less defined and depend on a complex interaction between potential increased vertical mixing under reduced sea ice and/or increased storminess, the robustness of the AO pycnocline, and lateral inputs of nutrients from marginal seas and shelves, along with the rivers inputs and erosion of those regions. These competing drivers will vary between different AO regions so that regional comparisons may serve as proxies for greater or lesser evolution of climate driven environmental change.

Detecting regional differences and decadal changes in primary production and nutrient availability requires regional comparisons of light availability, primary production and algal species composition, nutrient concentrations, hydrographic structure, and circulation on pan-Arctic scales and at synoptic time frames.

How will this be answered?

The SAS will collect quasi-synoptic, seasonally consistent data across the different arctic regions on:

- Size-fractionated (<5 µm and total) chlorophyll (phytoplankton standing stock) and nutrient concentrations at selected depths throughout the euphotic zone and deeper to sample the subsurface chlorophyll maximum together with profiles of light and hydrography to provide water column structure and water mass identification.
- Primary production over the euphotic zone and subsurface chlorophyll maximum measured using a range of techniques including on-deck incubations and analyses of different isotopes of dissolved gases such as oxygen and of the nitrogen/argon ratio.
- Phytoplankton composition to determine the sizes and types of the different primary producers.

These data can be analyzed to understand regional variability and how different regional drivers impact primary production, including whether nutrient availability is limiting primary production. Comparison between SAS data and both historical that are regionally and temporally coincident can lend insight into whether primary production is changing in magnitude and timing. Such historical data sets include work done from ice islands, the Trans-Arctic Section of 1994, the SHEBA program, the Shelf Basin Interactions program, Canada's Three Oceans program, the Distributed Biological Observatory, and many data collected at the central AO cruises of R/V Polarstern as well as in the Barents Sea by Norwegian vessels. Greater temporal context to the ship-based observations may be provided opportunistically from fluorometers and oxygen sensors deployed on platforms such as ice-tethered profilers and bottom moorings. In addition, SAS data can be compared to real-time data collections from other studies undertaken in the year of SAS occurs that might provide seasonal comparisons.

RQ5: Does northward range expansion of subarctic species vary regionally and are any of these species likely to establish permanent populations in Arctic regions?

One of the more intriguing potential changes to the AO ecosystem is its transformation from a purely Arctic system to one with sub-Arctic characteristics through the invasion and successful establishment of non-endemic species. This transformation could in the future support commercial and subsistence Arctic fisheries of sub-Arctic fish and invertebrates. It also could change the availability of prey to iconic upper trophic level animals such as marine mammals, including polar bears, seals, and walrus.

Rationale

Both eastern and western AO ecosystems can be impacted by the northwards range expansion of sub-Arctic species that migrate north into Arctic marginal seas and basins following recent warming of AO water masses, or that are carried north in the prevailing circulation, or that are carried into the AO in the ballast water of ships [e.g., *Bluhm and Grebmeier*, 2011; *Bluhm et al.*, 2015; *Wassmann et al.*, 2015; *Ware et al.*, 2016]. These sub-Arctic species, if they survive and establish populations, could potentially modify the composition and abundance of plankton, benthic organisms, and fish. Some organisms, such as toxic algal species that form harmful algal blooms or pathogenic microbes, may also impact fish, seabirds, and marine mammals and human communities through their use of marine organisms for subsistence or commercial hunting and fishing. Previous range expansions of deep water or benthic species may have resulted in the establishment of genetically distinct or isolated populations in the different basins, with potentially little exchange or connectivity between them.

The coccoid cyanobacteria *Synechococcus* is known to be associated with northward flowing warm water in the Chukchi Sea (Pacific Water) and in the eastern Fram Strait (Atlantic Water), with greater abundances at higher temperatures [*Nelson et al.*, 2014; *Paulen et al.*, 2016]. Small protists of Pacific origin also have been identified in the Beaufort Sea [*Lovejoy and Potvin*, 2011]. There are a number of recent reports of the presence of cells or cysts of previously unreported harmful algal species in the AO [e.g., *Gu et al.*, 2013; *Natsuike et al*, 2013; *Richlen et al.*, 2016] or the presence of their neurotoxins in subsistence marine mammals [e.g., *Lefebvre et al.*, 2016]. It has been suggested that some populations may be able to adapt to persist in the colder temperatures of the AO and therefore establish permanent populations, with future consequences to Arctic human communities that rely on marine resources (shellfish, mammals) for subsistence.

Several important copepod species from neighboring marginal seas are frequently observed in the central AO after being advected there in the prevailing currents [*Wassmann et al.*, 2015]. These include the subarctic species *C. finmarchicus* in the eastern AO and subarctic *Neocalanus* spp. and temperate *Eucalanus bungii bungii* in the western AO [e.g., *Ashjian et al.*, 2003; *Kosobokova and Hirche*, 2009; *Kosobokova and Hopcroft*, 2010]. In the western AO, distinct genetically differentiated populations of *C. glacialis* have been observed in the Bering/Chukchi Seas vs. the central AO [e.g., *Nelson et al.*, 2009]. Although sometimes observed in high abundance in the central AO (e.g., *C. finmarchicus*), these expatriates have not been believed to be able to successfully recruit and establish endemic populations there. For marginal seas such as the Barents and Chukchi Seas, whether the populations of *C. finmarchicus* and *C. glacialis* (respectively) found there represent endemic, self-sustaining populations or are re-introduced by the prevailing currents during each year remains unknown. Modeling studies focusing on the interplay of development rate, temperature, and advection for the *Calanus* species have suggested that warmer ocean temperatures may increase the range of endemic species but that substantial northward range expansion of established populations of subarctic species may not occur [*Ji et al.*, 2012; *Slagstad et al.*, 2011; *Feng et al.*, 2016]. Seabirds and marine mammals also are important indicators of northward expansion of subarctic species and of climate change [e.g., *Bluhm and Grebmeier*, 2011; *Bluhm et al.*, 2015].

Although expatriate species have been observed in the AO in many previous studies, it appears that their occurrence may be observed further to the north and at higher abundances than previously [e.g., *Ershova et al.*, 2015]. Whether this is the case and whether species can be transported from the Atlantic to the Pacific side or vice-versa remain unknown. Even benthic macrofauna has shown a northward shift in the last decade in dominant macrofaunal biomass south of St. Lawrence Island related to varying current patterns [*Grebmeier*, 2012; *Grebmeier and Cooper*, 2016]. This northward shift in the distributional pattern of benthic species, and subsequent changes in community composition has also been recorded at places in the Eastern AO [e.g., Svalbard Archipelago and Barents Sea; *Kortsch et al.*, 2015, *Jørgensen et al.*, 2017]. Increased northward expansion of the range of commercially important species of fish and invertebrates also has been observed [*Renaud et al.*, 2012; *AWI*, 2013; *Carothers et al.*, 2013; *Fossheim et al.*, 2015]. The question of whether ecosystems in the AO can sustain such populations over the winter is of interest to both Arctic and non-Arctic nations.

Understanding the potential establishment of expatriate species in the AO requires: a) Identification of pathways of immigration, b) Observation of expatriate species and of increases in abundance of those species, and c) Quantification of the ability of the species to survive and reproduce in the AO environment. Since historic data are temporally and spatially sparse in the central AO, there are few baseline observations for comparison with which to detect changes. This SAS thus will constitute baseline observations as the cornerstone for future efforts that will track change.

How will this be answered?

The SAS sampling effort towards this question will include:

- Determination of the species types, abundances, and population structures across multiple trophic levels including the benthos, using both traditional collection and identification approaches, particularly for zooplankton and larger organisms, and novel molecular techniques that can quantify composition and diversity of the microbial organisms. Samples will be collected using common protocols across the SAS "fleet".
- Experimentation to quantify species tolerances to AO conditions, focusing particularly on reproduction (e.g., zooplankton egg production), respiration, and grazing).
- Biological modeling.

Multiple aspects of RQ5 can be addressed with these measurements, although comprehensive understanding may only be achieved once additional surveys are conducted in the future. The presence and extent of expatriate species can be identified. Whether populations of different species are actively reproducing in the central AO can be assessed based on the presence of a full suite of life stages. Description of species' phenologies can identify synchronization of those life histories with production and prey species cycles. Pathways of immigration of expatriate species can be identified through association of species presence and abundances with ocean currents and water masses that will be defined through hydrographic measurements. Pan-Arctic comparisons will assess the relative vulnerability of different AO regions to ecosystem shifts resulting from expatriate colonization.

Experiments conducted during the same year and season across multiple AO regions will quantify species responses to the varying environments that may be proxies for various states of advancement of climate change. Modeling, particularly individually based modeling, can be used to explore northward range expansion and potential establishment of endemic populations of subarctic species [e.g., *Ji et al.*, 2012; *Slagstad et al.*, 2011; *Feng et al.*, 2016]. At present, the number of species for which we have suitable understanding of distributions and vital rates is relatively small. Both the survey data and rates from experimentation can be used to appropriately constrain model parameters and to apply those improved models for a wider range of species.

RQ6: How does biomass flow vary across regional ecosystems of the Arctic?

Ecosystem structures and how they impact the carbon cycle likely vary between different AO regions. A synoptic comparative approach can identify regional differences since seasonality will not be important. Regional differences in biomass, and carbon, flow will be important to regional differences in overall productivity from primary producers to the top trophic levels.

Rationale

As physical drivers change, species and size composition of pelagic and benthic communities, dominant species, and the relative number of different trophic levels may be modified, thus altering the flux of material including carbon through the ecosystem and the availability of prey for upper trophic levels such as fish, seabirds, and marine mammals. Ecosystem structure, including carbon pools and transformations, are undersampled and poorly defined for the central AO with very little work done on some of the trophic levels (e.g., bacteria, viral predators, microzooplankton, meiobenthos) that may have significant roles in carbon flow. Because the modification of environmental drivers by climate change differs between AO regions, variation in the impacts of biomass and carbon flow through the ecosystem can be expected on a regional scale, in turn leading to regional differences in the export flux of carbon to the seafloor and benthic communities and in the uptake or release of atmospheric CO_2 at the sea surface (see *Constable et al.* [2014] for a review of these concepts in the Antarctic marine and Southern Ocean environment and *Mathis et al.* [2014] for the AO).

Under ongoing climate change, modifications to the plankton could occur through changes in the physical or biological environment that would change the ability of species to recruit and persist. Warming ocean temperatures can also increase vital rates of poikilothermic organisms and the rates of biomass and carbon transformations between ecosystem components (e.g., changing grazing or respiration rates). This could change the community composition and dominance of the phytoplankton or micro- and meso- zooplankton, with potential shifts away from larger to smaller bodied species and subsequent impacts on their predators or grazers and on the supply of organic material to the benthos. Decreasing sea ice cover, increasing proportions of first year over multiyear sea ice, changes in snow cover and precipitation, nutrient availability, and greater areal coverage of melt ponds all have impacts on the timing and composition (e.g., relative contribution of ice algae vs. phytoplankton) of blooms [*Ji et al*., 2013; *Leu et al*., 2015; *Tremblay et al*., 2015]. The match-mismatch hypothesis has been advanced to describe how the life histories of the *Calanus* spp. copepods may, under climate change, no longer match primary production phenology under changing sea ice extent and seasonal timing, with potential negative impacts to the copepods and/or northward shifts in subarctic species [*Søreide et al*., 2010; *Leu et al*., 2011; *Wassmann and Reigstad*, 2011; *Ji et al*., 2012]. The impacts of changing environmental conditions on benthic communities in the central AO are relatively unknown, including the fate of export fluxes over the slope into the deep AO [*Kedra et al*., 2015].

Although significant work has been done in marginal seas and shelf systems, understanding of central AO standing stocks and species compositions for all ecosystem components is much less well defined. Furthermore, few biomass and carbon transformation rates are available for most central AO regions, making constraining ecosystem carbon budgets very difficult. The responses of AO organisms to changing temperature conditions also are very poorly understood as is the impacts on biodiversity.

How will this be answered?

Quantification of the biomass and carbon in the different ecosystem components and of the rates carbon transformations between components can be achieved for a number of important trophic levels during the SAS. The core measurements are common to addressing RQ5 above. Specific measurements include:

- Standing stocks and type or species composition of viruses, bacteria, archaea, phytoplankton, micro- and meso-zooplankton, fish, and benthic infauna and epifauna, and visual observations of seabirds and marine mammals (see also RQ5)
- Carbon and biomass transformations including respiration, production, consumption, and regeneration

These measurements, when synoptically conducted within a single season across multiple regions, will characterize standing stocks and transformations between key ecosystem compartments on a pan-Arctic basis. The data will also be invaluable for development, refinement, and validation of ecosystem models. The information also will contribute to the understanding required for RQ7-RQ9 focusing specifically on carbon.

CARBON CYCLE AND OCEAN ACIDIFICATION

Background

The global oceans significantly moderate climate change by absorbing heat and CO_2 from the atmosphere. Each year they absorb about a quarter of our CO_2 emissions [*Le Quéré et al.*, 2016]. Without this ocean sink of CO_2, the atmospheric concentration would now have been 560 ppm [*Khatiwala et al.*, 2013], far higher than the target of between 430-480 ppm required to achieve the targeted 2-degree limit of global warming with a 66% probability.

The absorption of man-made CO_2 by the ocean is driven by increased atmospheric CO_2 concentration resulting from fossil fuel burning, cement production and land use change. Ocean overturning is essential to maintain this large oceanic CO_2 sink because, it brings old water that has not been exposed to present atmospheric CO_2 levels to the surface ocean and that have capacity for absorbing anthropogenic CO_2. Ocean overturning also brings surface waters that have absorbed anthropogenic CO_2 to the deep ocean, where it is stored in the large volume of the abyss. Overturning is expected to decrease in the future, a result of increasing upper ocean stratification as temperatures rise. Ocean biogeochemical models consistently show that this will decrease the efficiency of the ocean sink [*Friedelingstein et al.*, 2006]. However, critically, the magnitude of the decrease differs significantly among models because the processes causing overturning are poorly understood and difficult to reproduce numerically. Progress on these aspects is essential for future policy planning.

Climate change may not only decrease ocean uptake of anthropogenic CO_2, it also may mobilize the large reservoirs of natural carbon in the ocean (Table 1). Even a small relative perturbation of these natural ocean reservoirs could lead to outgassing or in gassing significantly impacting the atmospheric reservoir and CO_2 concentration. For example, the regular occurrence of ice-ages over the past few million years is largely a consequence of perturbations of the oceanic carbon reservoir [e.g., *Sigman and Boyle*, 2000]. Further understanding of the resilience of the natural carbon inventory in the ocean to climate change is needed for accurate projections of climate change.

Table 1. Global atmospheric and marine carbon reservoirs in the units of Giga tons C (Gt C). Carbon in the atmosphere exists primarily in the form of CO_2, while in the ocean it exists in the forms of Dissolved Inorganic Carbon (DIC), Dissolved Organic Carbon (DOC) and Particulate Organic Carbon (POC). Human emissions of anthropogenic carbon increase the inventory of CO_2 in the atmosphere and the DIC inventory in the oceans.

	Natural	Added anthropogenic carbon
Atmosphere	CO_2: 600	CO_2: 200
Ocean	DIC: 38 000 DOC: 700 POC: 3	DIC: 150 DOC: - POC: -

The AO plays a key role in the partitioning of carbon between the upper and deep ocean. The production of AO deep waters not only transports anthropogenic CO_2 away from the surface ocean, it also helps regulating the surface-to-deep ocean gradient—hence, the reservoir—of natural carbon in the global ocean. Further, vast amounts of permafrost carbon (in the form of methane and organic carbon) are stored in the Arctic shelf seas and surrounding land masses, these may be mobilized under global warming. The AO will be one of the main conduits for this carbon into the atmosphere-ocean system.

The current net uptake of fossil fuel CO_2 affects ocean chemistry and leads to ocean acidification, which may seriously affect marine ecosystems. Briefly, CO_2 exists in seawater as DIC in the forms carbonic acid (H_2CO_3), bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}). The latter two are bases while the first (H_2CO_3) is an acid. Globally, 19 out of every 20 CO_2 molecules that now enter the ocean react with the strongest base (carbonate ion) to make bicarbonate ion.

$$CO_2 + CO_3^{2-} + H_2O \rightarrow 2HCO_3^- \tag{1}$$

The net effect is to lower the concentration of carbonate ions and to decrease the pH since CO_3^{2-} is a stronger base than HCO_3^- and also 1/20 CO_2 molecules are hydrolysed to carbonic acid.

The AO is particularly sensitive to ocean acidification because of its low seawater temperatures. The cold water has high CO_2 solubility and thus the natural concentration of inorganic carbon is large as is the concentration of carbonic acid. From the reaction described above it follows that the concentration of carbonate ions will be low in this system, and it takes only a relatively small amount of additional CO_2 (e.g., from uptake of fossil fuel CO_2) to make the waters undersaturated with regard to calcium carbonate. Also, the low concentrations of carbonate ions mean that the carbonate buffer capacity is low (high Revelle factor), hence this is one of the regions where the greatest pH change as a consequence of ocean acidification will be seen.

Ocean acidification has been shown to have detrimental effects on many forms of marine life. For example, neurotransmission is affected so that many organisms, including some species of fish, exhibit behavioral changes when exposed to pH levels expected at the end of this century under 'business as usual' CO_2 emission scenarios. The loss of carbonate ions also threatens calcifying organisms such as corals, coccolithophorids and pteropods. The energy cost of calcification is greater as ocean acidification increases so that it becomes harder to maintain reef or shell structures. At high enough acidification, these structures may simply start to dissolve. The extent of ocean acidification and the sensitivity of key organisms are decisive drivers for future marine ecosystem structure, production and harvestability. Thus, the present and future magnitude and impacts of ocean acidification need to be quantified to accurately understand and manage future AO ecosystems.

With this in consideration we identify three research questions that are particularly important to constrain, not only for AO but also for global science and policy development. The first of these can be largely resolved with the data collected at the SAS, for the second the SAS will provide a basin wide overview that can be augmented with seasonally resolved process studies, and for the third the SAS will provide relevant boundary conditions for experimental work and also a baseline for tracking OA and its impacts in the region in the years and decades to come.

Research questions:

RQ7: What is the contribution of the Arctic Ocean to maintaining the global ocean carbon dioxide reservoir and uptake?

RQ8: What are the input and fate of terrestrial and subsea carbon to the Arctic Ocean?

RQ9: What are the magnitude, drivers, and impacts of Ocean Acidification in the different regions of the Arctic?

RQ7: What is the contribution of the Arctic Ocean in maintaining the global ocean carbon dioxide reservoir and uptake?

The AO has special significance to the global carbon cycle because of its low temperatures and the ice-cover. The warming and loss of sea ice makes it especially sensitive to climate change.

Rationale

Arctic sea ice formation in numerous polynyas along the AO continental margins [*Tamura and Ohshima*, 2011] results in brine formation that efficiently transports carbon from surface water to the deep (Fig. 5). Carbon is rejected from the sea ice during its formation and the resultant dense brine, enriched with carbon, subsequently sinks. In polynyas, surface cooled waters continue to take up atmospheric CO_2, rich in anthropogenic carbon, during ice formation. Therefore, brine production can contribute not only to transport of carbon from the surface to depths but also to the flux of CO_2 from the atmosphere to the surface ocean so that an efficient atmosphere to ocean CO_2 pump is established [*Omar et al.*, 2005; *Anderson et al.*, 2004; *Miller et al.*, 2011; *Else et al.*, 2012].

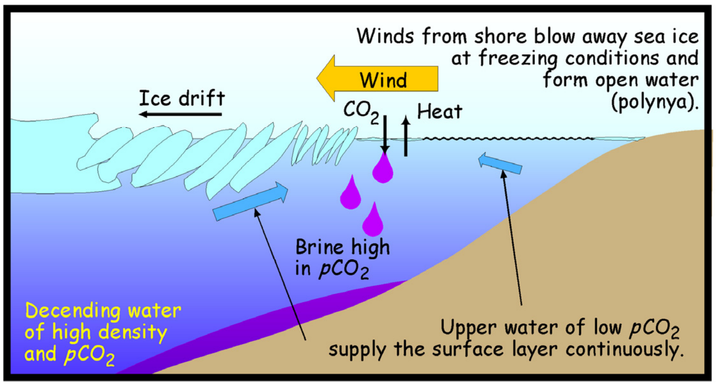


Figure 5. Distribution of known polynyas [*Meltofte*, 2013] and schematic of ice, brine and carbon export processes in polynays.

Existing seasonal and perennial sea-ice cover, on the other hand, is an efficient boundary for air-sea CO_2 uptake. Hence, large areas of surface waters in the central AO are presently undersaturated with CO_2 relative to the atmosphere and are potential CO_2 sinks. The undersaturation is due to the cooling, which lowers the partial pressure of CO_2 of inflowing surface waters from the Pacific and the Atlantic, to CO_2 uptake by primary production in the "inflow-shelves" [*Carmack and Wassmann*, 2006], and to isolation of the surface waters from the atmosphere by the sea ice boundary.

Sea-ice cover also limits primary and, consequently, export production in the deep basins of the AO. Thick ice and snow cover act as efficient barriers to sunlight, required for photosynthesis, to the upper ocean. In addition, they insulate the ocean from the extreme winter heat loss and limit transfer of momentum from strong winds, which would otherwise lead to vertical mixing and replenishment of upper ocean nutrients. As a result, the deep basins of the AO are oligotrophic systems.

The shelf seas, on the other hand, are seasonally ice-free and highly productive ecosystems. In particular the Barents and Chukchi Seas are 'inflow-shelves' [*Carmack and Wassmann*, 2006] which receive nutrient rich water from the Atlantic and Pacific Oceans. Consequently, these two areas host some of the most productive ecosystems of the global oceans. In contrast, primary production on the interior- and outflow- shelves relies on upwelling of nutrient rich arctic boundary currents, which flows around the shelf edge submerged by the fresher surface waters, as well as on input of nutrients from the rivers.

Over the past decades, unprecedented changes in both sea-ice thickness and extent have taken place. While an ice-covered deep-basin was the past normal, a large fraction is now free of ice in summer. In 2012, 40% of the deep basins were ice free in September (Fig. 6). The loss of summer sea ice is expected to be aggravated with climate change, but the winter-ice may be more resilient, at least in the central part of the AO. As a net result, a seasonally ice-covered AO is expected in a future warmer climate. Under this scenario, brine production will increase, affecting intermediate and deep-water production and the associated vertical transport of both anthropogenic and natural carbon; air-sea CO_2 exchange will be enabled over a larger area; and the increased access to light and nutrients will lead to more extensive primary and export production.

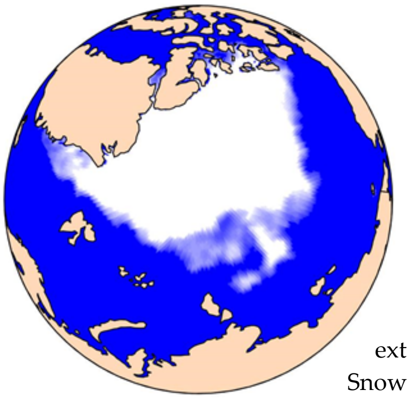


Figure 6. Arctic sea ice concentration September 2012, extracted from National Snow and Ice Data Centre.

Together, these changes will impact the contribution of the AO towards maintenance of the global ocean carbon dioxide reservoir and uptake. In order to understand the potential implications of changes in ocean carbon storage the present state and driving processes must be accurately quantified and identified; i.e. the magnitude and components of the AO carbon budget must be quantified.

While estimates of large scale AO carbon uptake and physical and biological transformations and transports exist, they have unacceptably large uncertainties. *Olsen et al.* [2015] synthesized published estimates [e.g., *McGilchrist et al*., 2014; *Tanhua et al., 2009; Bates and Mathis,* 2009] of carbon transport across the four gateways (Davis Strait, Fram Strait, Barents Sea Opening and Bering Sea), air-sea fluxes, riverine transports and storage (of anthropogenic) carbon in the AO (Fig. 7. and Table 2). In the present state, a closed budget has not been quantified, even when considering the large uncertainties. This is a consequence of the sparse and fragmented underlying data. For internal transports (both in the horizontal and in the vertical) mediated by ocean circulation and biological processes, even less is known.

How will this be answered?

SAS will provide data on carbon concentrations across all gateways and in all basins of the AO. These data will be used together with estimates of volume fluxes, for example from an inverse model [*Tsubouchi et al*., 2012], to constrain the inventory of DIC in the AO and the fluxes across the gateways. Data from moored current meter arrays (e.g., Hausgarten) may provide additional constraints on the volume fluxes. The anthropogenic component will be separated from the natural component using estimates of C_{ant} determined using the TTD method, based on transient tracers, SF_6 and CFC-12 as measured at the SAS. Vertical carbon fluxes will be determined using Oxygen Utilisation Rates [*Sonnerup et al*., 2013], information from sediment traps for biological sinking fluxes, and volume conservation principles [*MacGilchrist et al*., 2014] for physically mediated fluxes. It is not unlikely that local Total Matrix Intercomparison approaches may be used as well [*Gebbie and Heybers*, 2010].

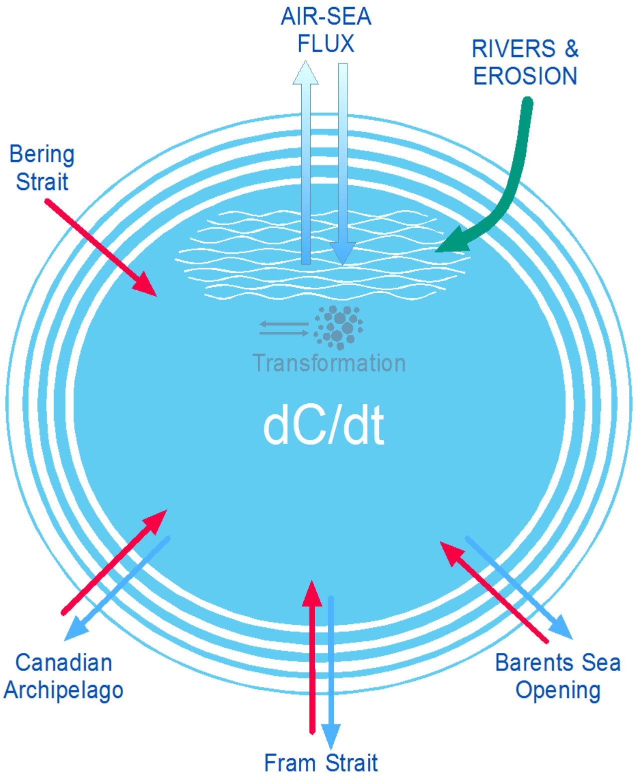


Figure 7. Schematic illustration of the Arctic Ocean carbon budget, including the exchange with surrounding oceans, atmosphere and land (rivers and erosion), as well as the biogeochemical transformation and storage (dC/dt) term. (Figure after *Olsen et al*, 2015.)

Table 2. The Arctic Ocean Carbon Budget from *Olsen et al.* [2015]

	Present day (Tg C yr^{-1})	Anthropogenic (Tg C yr^{-1})	Preindustrial (Tg C yr^{-1})
Net ocean transport	-231±49[a]	~29[c]	~-202
Land & river Sources	65±6	0	65
Air-sea flux	133±66[b]	~26[d]	~107
Storage	-55±7[c]	-55±7[c]	0
Transformation	~0	~0	0
Sum	-88±83[e]		~-30

[a] From *MacGilchrist et al.* [2014]

[b] From *Bates and Mathis* [2009]

[c] Calculated in this contribution

[d] Determined as the difference between the net transport and storage terms. Any uncertainty in net transports has not been considered.

[e] The root sum of square of stated uncertainties.

RQ8. What are the input and fate of terrestrial and subsea carbon to the Arctic Ocean?

Global warming may mobilize OC presently stored in terrestrial and subsea permafrost zones surrounding the AO. Additionally, large pools of fossil methane exist on the seabed in the shelf seas that may be liberated with under warming and sea ice reduction. These pools represent a very strong potential global warming feedback and the AO will be one of the main conduits of this carbon to the ocean-atmosphere system.

Rationale

The AO currently receives about 11% of global runoff [*Lammers et al.*, 2001], although it represents only about 1% of the world ocean's volume. The drainage basin area (~24×10^6 km^2) of the rivers entering the AO is twice as large as the AO itself (Fig. 8), and includes extensive permafrost regions. Presently rivers add large amounts of terrestrial organic carbon to the Arctic shelf seas during the summertime thaw. Additionally, reduced sea-ice cover in summer increases coastal erosion by high seas during storm events; this input of organic carbon can be of the same order of magnitude as that added by rivers [*Stein and Macdonald*, 2004].

This organic carbon is delivered as dissolved (DOC) and particulate organic carbon (POC). Both forms can be oxidized to CO_2 in seawater by microbial and photochemical degradation processes and can escape to the atmosphere. A fraction of the DOC from both marine production and terrestrial sources is processed rapidly in the surface waters. The remainder persists long enough to be entrained into subsurface halocline waters in conjunction with ice formation and brine rejection. Eventually much of it is exported to the Atlantic and global oceans and mineralized there [*Anderson and Amon*, 2015]. The long-distance transport of POC in contrast, is limited. It sinks out of the surface layer and is either respired to CO_2 at depth or buried in the sediments.

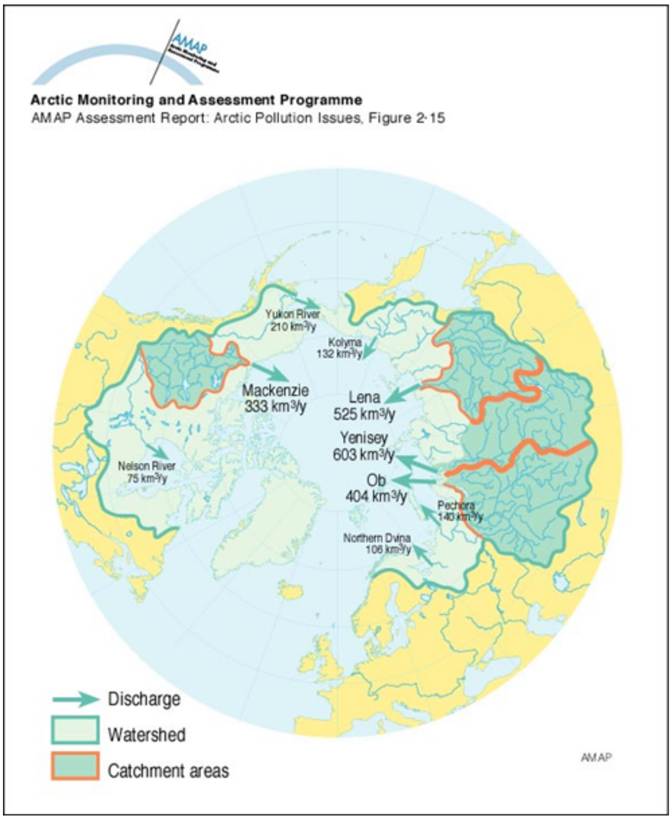


Figure 8. Arctic Ocean watershed and Catchment areas of the largest rivers and annual runoff (km^3 yr^{-1}) [*AMAP*, 1998]

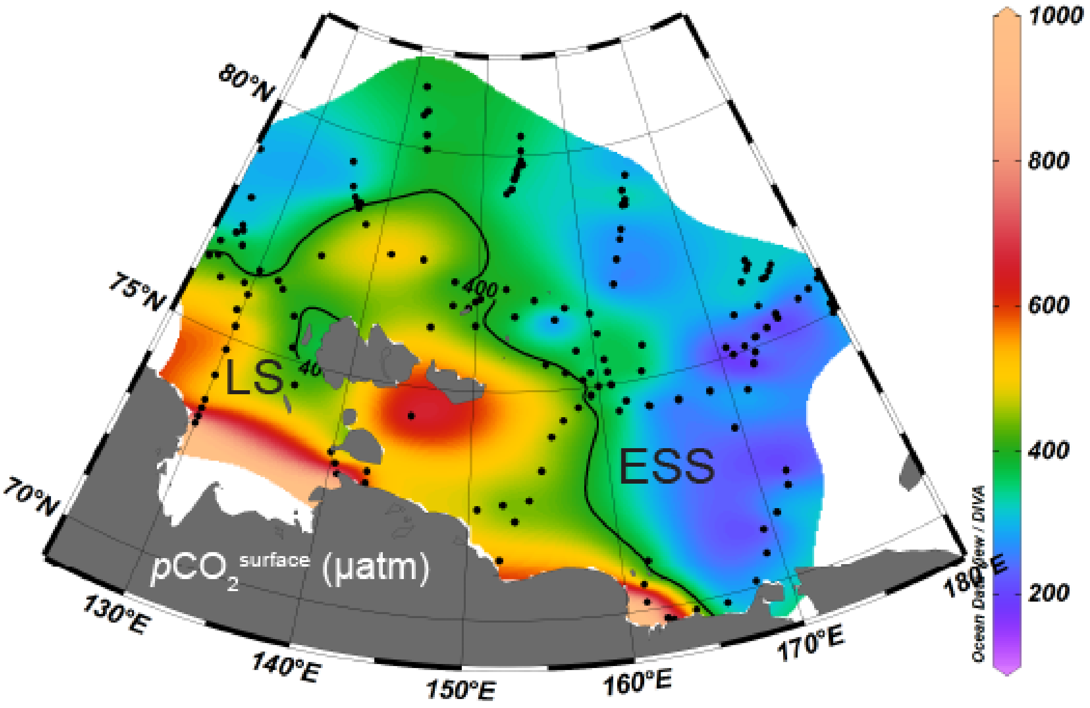


Figure 9. pCO_2 in the surface waters of the Laptev Sea (LS) and East Siberian Sea (ESS) as observed in 2008 and 2014. The isoline of 400 µatm indicates the atmospheric level.

The imprint of terrestrial organic carbon oxidation is readily apparent on the AO shelves. During the International Siberian Shelf Study 2008, surface waters were supersaturated with CO_2 in mid-summer, despite complete nutrient utilization through pelagic primary production that normally would lead to strong undersaturation [*Anderson et al.*, 2009]. These conditions, which lead to CO_2 outgassing, also were supported by data from the outer shelf collected during the SWERUS-C3 expedition 2014 [*Anderson et al.*, 2016] (Fig. 9).

Large quantities of the potent greenhouse gas methane are trapped in the subsea permafrost on the AO Shelves. It has been estimated that about 540 Gt of methane is trapped in the form of chlathrates (methane hydrates) and 360 Gt as free gas in the East Siberian Arctic Shelf (ESAS) subsea permafrost [*Shakova et al.*, 2010a], which holds ~80% of all subsea permafrost globally [*ACIA*, 2004]. This reservoir was formed during the last glacial, when global sea level was about 100 m lower than today and has subsequently been submerged. The methane can escape from the permafrost through thaw columns or bulbs. In the water column, some of this is oxidised to CO_2 while some escape directly to the atmosphere [*Biastoch et al.*, 2011]. Outgassing of methane has also been documented recently [e.g., *Shakova et al.*, 2014; *Thornton et al.*, 2016]. However, while the measurements certainly agree that methane outgassing is larger in the ESAS than in other shelf seas, estimates based on observations of the release at the seafloor suggest an outgassing that is 6 times larger than determined from actual air-sea methane flux measurements. In any case, destabilisation of the Arctic permafrost is likely to aggravate global warming.

An increasing body of evidence shows ongoing widespread Pan-Arctic permafrost thaw [e.g., *Smith et al.*, 2005; *Liljedahl et al.*, 2016]. As global warming continues this will exacerbate. Together with the expected increase in precipitation, a significant amount of the mobilized OC will be transported in rivers to the Arctic shelf seas. Further additional organic carbon input will come from enhanced coastal erosion [*Stein and Macdonald*, 2004]. Release of subsea methane is also expected to increase, following ice loss and increasing water temperatures [*Shakova et al.*, 2010b]. Given the exceptional potential for positive feedbacks on the climate system associated with release of terrestrial and subsea carbon to the AO, the rates of release must quantified as well as the factors governing the further degradation of organic carbon to CO_2.

How will this be answered?

The Pan-Arctic coverage of the CO_2 produced from decaying terrestrial organic carbon will be made possible by data collection on the shelves, as well as basin-wide, of the carbon system in combination with $d^{13}C$ and nutrient/oxygen. Also, the distribution of DOC will be determined in order to evaluate its refractory components. In addition to the geographic distribution of terrestrial organic carbon signatures, it would be useful to determine the oxidation rates of the various organic compounds depending on the environmental characteristics (such as temperature) by incubation experiments.

The spatial variability of methane outgassing will be determined during the cruises in the shelf seas, as well as along the continental margins of the basins, by acoustic methods. These will be complemented by determination of the methane concentrations in the water column. It would be favorable to supplement these measurements with atmospheric ones in order to determine the air-sea fluxes.

RQ9: What are the magnitude, drivers and impacts of Ocean Acidification in the different regions of the Arctic?

Critical OA thresholds have already been passed in some regions of the AO. Within the next few decades most other regions will follow suit with potentially serious impacts on marine organisms. Yet, the actual ecosystem impacts are still virtually unknown.

Rationale

The AO ecosystems are uniquely adapted to the cold, hostile and seasonally highly variable conditions that have prevailed for the past millions of years. Human driven changes are now transforming these boundary conditions at rate that is likely outpacing evolutionary capacity at species level, as a result species invasion and extinction is likely to become more prevalent. Ocean acidification is of particular concern given the low buffer capacity of the Arctic Ocean's inorganic carbonate chemistry. The concentration of carbonate ions is low and the calcium carbonate saturation is quite sensitive to additional CO_2 absorption. Waters undersaturated in aragonite has already been observed in some regions of the AO [*Yamamoto-Kawai et al.*, 2009, 2011; *Bates et al.*, 2009]. Aragonite is a form of $CaCO_3$ mineral, precipitated by many organisms (e.g., *pteropoda*) to build shell (i.e., pteropods) or reef structures (i.e., corals). Undersaturation of calcium carbonate is a critical threshold for these organisms, leading to significant stress and eventual dissolution of the $CaCO_3$ matrix. The situation is further aggravated by a predicted increase in precipitation and run off, and more widespread seasonal ice melt. This adds low buffer capacity freshwater to the system. Terrestrial run off also adds organic carbon, as discussed above, a fraction of which is oxidized to CO_2 that increases the OA. As a result of all this, widespread surface ocean aragonite undersaturation is expected to occur in the next decades [*Steinacher et al.*, 2009].

Ocean acidification has also been shown to affect the sensory abilities and behavior of many marine species, including fish, with potential effects on predator-prey relationships. In a recent study, survival of Barents Sea cod larvae was observed to decline under increasing OA [*Stiasny et al.*, 2016]; mortality doubled when larvae were exposed to OA conditions expected by the end of the century under business as usual emission scenarios. Thus, OA may have significant negative effects on recruitment and harvestability of this economically very important species.

Ocean acidification is just one of several environmental changes with potential ecosystem impacts that is occurring with climate change and increasing human presence. In the AO, warming and disappearance of the perennial sea ice is of particular relevance, with attendant impacts on biogeography, light availability, vertical mixing and nutrient availability. Added to this are the potential effects of increased run off from land, this will affect the freshwater distribution, haline stratification and turbidity, and may also be an increased source of nutrients to the AO. Finally, increases in shipping and extraction of natural resources leads to a higher risk of pollution.

While the absorption of anthropogenic CO_2 and resulting ocean acidification of surface waters is fairly straightforward to project under different CO_2 emission scenarios in most ocean regions [*Bopp et al.*, 2013] the large number of feedbacks makes it much more complicated for the Arctic. Sea-ice melt, organic carbon added by terrestrial run-off and its oxidation in the water column, subsea permafrost methane release and oxidation [*Biastoch et al.*, 2011] and increased upwelling and primary production all need to be adequately understood and represented for realistic projections. There is an urgent need for knowledge as these amplifying effects may cause unacceptable Arctic OA even under low CO_2 emission scenarios.

There is growing recognition that organismal response to OA as observed in perturbation experiments cannot be directly used to predict the future of marine ecosystems. This will be dictated by the combined set of changes in environmental boundary conditions, ecosystem structure and the adaptive capabilities of the various species [*Riebesell and Gattuso*, 2014]. On one hand this calls for extensive multifactorial and long-term perturbation experiments, on the other it implies that the actual consequences will be apparent likely only after they have emerged in the real world. It is therefore important to determine current environmental boundary conditions and tolerance limits of Arctic marine ecosystems.

How will this be answered?

The simultaneous collection of hydrographic, chemical and ecosystem data will make it possible to advance our knowledge on these issues. The OA status will be determined in the different regions of the AO from the carbon system data as described in RQ7. The contribution to AO from anthropogenic emissions is evaluated using the TTD method, based on transient tracers, SF_6 and CFC-12 (RQ7), while the amplifying effects of terrestrial and subsea carbon sources is taken from RQ8. The combination of the observed standing stocks and type or species composition in relation to OA conditions add information of current environmental boundary conditions for the different ecosystems. This will be especially critical in areas with naturally low pH as in the coastal regions where much organic matter decay to produce high pCO_2 levels. The combinations of all these data and relevant processes establish the basis for model projections of future environmental conditions.

IMPLEMENTATION

The focus of the Synoptic Arctic Survey is on the set of planned full depth sections that will provide the Pan-Arctic coverage of observations required to address the science questions addressed earlier. This chapter summarises overarching aspects of its envisioned implementation.

Planned Sections

The planned set of sections (Fig. 2) are positioned to cross known oceanic regimes and currents and to be consistent with suitable historic sections. They include the major straits and neighboring oceans (the Barents Sea Opening and Bering, Davis and Fram Straits), one or more sections across each shelf sea (the Barents, Kara, Laptev, East Siberian Shelf, Chukchi, Beaufort, and Lincoln Seas and the Canadian Archipelago), and sections across the deep basins (Nansen, Amundsen, Makarov and Canada) and the ridges separating them. Sections are also planned along the East Siberian Shelf Edge. It is important that the sections intersect each other at several locations to enables estimate of sampling and measurement bias using crossover and inversion analysis [*Tanhua et al.*, 2010; *Olsen et al.*, 2016]. Our recommendation is that common station locations placed at the junctions of intersecting sections be sampled by all ships occupying those sections.

Station spacing for CTDs should preferable able to resolve the Rossby radius of deformation. However, as this radius is very small, ~5-15 km depending on region [*Nurser and Bacon*, 2014] we suggest 20 nm between stations as a compromise to ensure that sufficient time is available on the cruises to achieve broad Pan-Arctic spatial coverage. Closer spacing should be used over the ridges and at shelf slopes where boundary currents are present. Sampling of chemical variables should ideally be carried out at every CTD station; however, some flexibility can be allowed in order to enable sample analysis to keep up with collection. For example, sampling of water for chemical analyses at every second CTD station may be adequate over the deep basins. Both benthic and water column communities will be sampled for the ecosystem investigations. Water column sampling will occur every other CTD station, with sampling at 25 m of bottom depth, at every 50 m between 50 and 200 m, at every 100 m of water depth between 500 and 1000 m, while deeper than 1000 m sampling at every 500 m should be sufficient.

Bottle sampling resolution for chemical parameters and viruses, bacteria and archaea, phytoplankton, and microzooplankton should be high in the upper water column where variability is largest. In deep and bottom waters, greater vertical spacing is sufficient except for very close to the bottom where resolution should be high in order to observe chemical gradients caused by organic matter decay. Suggested bottle sampling depths are provided in Table 3. Vertical discrete sampling for larger plankton and fish is desirable and can be achieved through net systems that can collect vertically discrete samples (e.g., Hydrobios Multinet) and, particularly in the upper water column, optical and acoustic systems. Benthic sampling will occur both on the slope and deep basins using a multi-corer and/or box corer.

Equipment

The ships taking part in the Synoptic Arctic Survey should be equipped to record underway navigation, bathymetry, near-surface water properties (e.g., chlorophyll fluorescence, dissolved oxygen, pCO_2), water column velocity, and meteorological data. Water sampling should be conducted using a Rosette sampler equipped with a freshly calibrated CTD. The Rosette sampler should be large enough to accommodate at least 24 10-L Niskin or Go-Flo bottles to minimize the need for duplicate casts and save ship time. The CTD will provide conductivity, temperature, depth and (derived) salinity data approximately every meter in the water column. The CTD package should be equipped with sensors at the very least for oxygen, fluorescence, transmission and PAR to provide greater resolution on the vertical distributions of the chemistry and biological production than from the water samples. Inclusion of an ADCP on the rosette to measure full water column velocities and estimate mixing in the ocean [e.g., *Kunze et al.*, 2006] also is recommended.

Table 3. Suggested depths of sampling of water for physical, chemical and ecosystem parameters. For some of the parameters a subset of these depths might be relevant for science or practical reasons.

No.	Depth (m)	No.	Depth (m)	No.	Depth (m)	No.	Depth (m)
1	10	7	100	13	400	19	2500
2	20	8	125	14	500	20	3000
3	30	9	150	15	700	21	3500
4	40	10	200	16	1000	22	4000
5	50	11	250	17	1500	23	bottom-50
6	75	12	300	18	2000	24	bottom

While the chemical properties of the seawater and the composition and abundance of the smaller plankton (viruses, bacteria/archaea, phytoplankton, microzooplankton) can be fully determined through analyses of water samples drawn from the Niskin/GoFlo bottles, other ecosystem measurements require nets, corers and acoustic and optical instrument.

Measurements

The recommended set of measurements is presented in Table 4. This is grouped into physical, chemical and biological measurements, in large part to simplify alignment with the strategies of existing coordinated observing programs. The measurements themselves will be used in an interdisciplinary effort to tackle the research questions presented earlier in this plan (e.g., chemical tracers can be used to determine ocean circulation structure and rates as well as anthropogenic carbon, and information on ocean structure is needed to understand the regional variability of biological systems).

Under optimum conditions all measurements should be carried out at all ships using common sampling and analytical techniques, however some of the measurements are more relevant for the shelf and boundary regions and less relevant in the deep basins. This further detailed in the following text.

The sampling strategy for the physical and chemical measurements on the SAS follows the recommendations of the Global Ocean Ship-Based Hydrography Investigations Program (GO-SHIP) that routinely monitors the global oceans. We recommend that the set of GO-SHIP Level 1 measurements is carried out on all cruises, but with some modifications to better fit conditions in the AO and the main goals of the SAS.

Physical and chemical measurements

Salinity and oxygen measurements will be used to calibrate the CTD-mounted sensors and should preferably collected at every Niskin sampling depth, in accordance with GO-SHIP recommended practices [*Hood et al.*, 2010]. Although salinity samples, in contrast to oxygen, can be stored, it is preferable to analyse both types of samples on board to enable quality control of CTD sensors and Niskin bottle performance during the cruise.

Seawater CO_2 chemistry should be measured at all cruises. It is described by four variables, Dissolved Inorganic Carbon (DIC), Total Alkalinity (TA), pCO_2 and pH. At last two of the four needs to be measured to obtain a full description of the CO_2 chemistry, ocean acidification and to enable calculation of the two that aren't measured. The measurements should be conducted according to *Dickson et al.* [2007], preferably on-board in order to minimize risk of sample degradation during storage.

The nutrients nitrate, phosphate and silicate should be measured at all cruises, preferably using gas segmented continuous flow analysers [*Hydes et al.*, 2012], i.e. auto-analysers. When properly maintained and operated these provide nutrient data of highest quality, but Reference Materials for Nutrients in Seawater (RMNS) should be measured by each participating group to actually ensure this. The nitrate analysis involves a reduction step so that it is actually nitrate+nitrite that is measured. Measurements of nitrite enable separation of these two. Ammonium may be measured as well, but normally requires a dedicated instrument. Nutrient samples may be frozen and analysed ashore but are preferably analysed at sea as this gives more reliable data. In case of storage, the adequacy of the conservation procedure(s) needs to be well documented.

For the halogenated transient tracers, we recommend that at least SF_6 and CFC-12 be measured. The data are highly valuable for understanding not only rates of ventilation, but also anthropogenic carbon storage and biogeochemical transformation rates and should be measured at all cruises. They are measured on board.

Both Particulate and Dissolved Organic Carbon should be measured. The measurements are particularly important on shelves and at the shelf breaks where the terrestrial organic material enters the AO. In addition, DOC should be measured at the sections across the gateways to quantify the export to the global ocean. POC measurements in deep basins are valuable for determination of remineralisation length scales.

The ratio of the stable isotopes ^{18}O and ^{16}O in water, expressed as $\delta^{18}O$, is very useful for water mass mixing analyses in the AO. Samples should be collected at all cruises but can be analysed ashore.

Methane measurements should in particular be carried out on the sections covering the ESAS region. Methods for preservation of dissolved methane samples exist, even without the need for $HgCl_2$ [*Magen et al.*, 2012], but the samples should preferably be analysed on-board to minimize uncertainties.

There are several other variables of interest but not essential for the SAS scientific goals. These include $\delta^{13}C$ of DIC, Dissolved Organic Nitrogen, ^{14}C, Helium-Tritium etc. As far as possible, such additional water column measurements should be accommodated. Operation of autonomous instruments for surface ocean measurements is also advantageous. Such instruments exist for many variables, for example are temperature, salinity, pCO_2 and fluorescence sensors widely used. For the shelf seas, underway methane measurements are of particular interest.

Table 4. Recommended set of measurements for SAS cruises. When possible, samples will be collected at sea and analysed post-cruise in laboratories on land.

Variable	Sampling	Target Accuracy If Applicable
Physical and chemical measurements		
Pressure	CTD	3±0.5dbar
Temperature	CTD	0.002±0.0005°C
Salinity	CTD + Niskin	0.002±0.001 g kg^{-1}
Dissolved Oxygen	CTD + Niskin	±1%
Nutrients (NO_3/NO_2, PO_4, SiO_3)	Niskin	1-3±0.2%
CFCs and SF_6	Niskin	1-2±1%
Dissolved Inorganic Carbon	Niskin	±2 µmol kg^{-1}
Total Alkalinity	Niskin	±3 µmol kg^{-1}
pH	Niskin	±0.005
$\delta^{18}O$ of H_2O	Niskin	
Methane	Niskin	
Dissolved Organic Carbon (DOC)	Niskin	
Particulate Organic Carbon (POC)	Niskin	
Water column ecosystem measurements		
Chlorophyll	Niskin	
Primary production	Incubation	
Viruses	Niskin	
Bacteria	Niskin	
Phytoplankton composition	Niskin	
Microzooplankton	Niskin	
Meso-and Macro- zooplankton	Bongo nets, Multinet, Optical Instruments, Acoustics	
Icthyoplankton	Aluette or Tucker Trawls, Acoustics	
Fish	Trawls, Acoustics	
Marine mammals	Passive acoustics, Visual observations	
Other Carbon transformation rates	Selected process studies (e.g., grazing, reproduction, sinking, respiration)	
Benthic measurements		
Meio- and Macro- fauna	Box Core or Multicore or other corers	
Epifauna	Benthic camera, Beam trawl	
Other Carbon transformation rates	Selected process studies (e.g., grazing, reproduction, sinking, respiration)	
Other		
Epontic Communities	Under-ice imaging, ice cores, sub-ice sampling	
Seabirds	Visual Observations	

Biological measurements

The recommended set of biological measurements is suitable for (1) quantifying the different biological carbon stocks and the species composition, dominance and size structure in pelagic and benthic trophic levels and ecosystem compartments and (2) establishing trophic linkages and carbon flows between trophic levels (e.g., primary production, grazing, and carbon export flux). All of these measurements need to be interpreted in the context of the physical environment (hydrography, currents) and are directly linked to parameters required for an understanding of the AO carbon cycle.

Establishment of the different biological carbon stocks and composition can be accomplished by collecting samples that can be analysed post-cruise in home laboratories. Samples for water column virus, bacteria/archaea, phytoplankton, and microzooplankton abundance and composition can be collected using the Niskin/GoFlo bottles on the CTD rosette or from underway science seawater flows and preserved for microscopic enumeration, molecular analyses that reveal diversity and composition (e.g., use of DNA "bar codes"), or for pigment composition (phytoplankton). Phytoplankton standing stock should be estimated from extracted chlorophyll optimally on-board ship. Samples for meso- and macro-zooplankton, ichthyoplankton, and fish should be collected using appropriate net sampling systems (e.g., Hydrobios Multinet, Bongo nets, mid-water trawls) both from the water column and under-ice. These samples would be preserved at sea and enumerated post-cruise except for the fish samples that may be enumerated at sea. Vertical distributions and composition for these taxa also should be quantified using acoustic instruments (e.g., hull-mounted, towed, or profiling multifrequency acoustics, video plankton recorders, the LOKI, or UVP). Benthic infauna, including bacteria/archaea and viruses, would be collected using corers and grabs and preserved for later enumeration (larger infauna would be sieved out of the mud prior to preservation). Benthic epifauna would be collected using trawls or quantified using optical instruments with samples enumerated at sea. Epontic and in-ice taxa should be surveyed using under-ice trawls and optical instruments and ice cores; samples from the ice cores would be treated for each taxonomic type similarly to those from the water column.

Trophic linkages between different ecosystem components should be established using direct measurements of key rate processes such as primary and secondary production and grazing (at-sea incubations) and quantification of parameters that describe trophic structure such as stable isotopes and molecular analyses of gut DNA. Carbon export should be estimated using short-term sediment traps, particle size composition and sinking rate from optical instruments, and direct measurements of fecal pellet production and sinking rates.

Adjoint Observations and Activities

While the hydrographic sections represent the core activity of the SAS, several additional activities will complement these and provide valuable information to answer the Research Questions. Even if these other activities are outside the direct SAS field study we see synergies in the science that are briefly summarized in this section. Furthermore, there might be opportunities to use the SAS cruises to support long time observation platforms when those activities do not interfere with the main program.

Eularian and Lagrangian observations

Eularian and Lagrangian observations are collected from moored and drifting platforms, respectively. They have the advantage of autonomous operation and are increasingly being deployed in the AO. Examples of Eularian observatories include the Hausgarten mooring array in the Fram Strait, the A-TWAIN array just north of Svalbard, and the many moorings deployed as part of the DBO. Examples of Lagrangian observatories include Ice Tethered Profilers—the Argo of the Arctic [*Toole et al.*, 2011]—and now also actual Argo drifters as ice sensing algorithms and subsea positioning systems become available.

The Eularian and Lagrangian observatories rely on sensor technologies for collecting their data and there are typically issues with calibration and drift. The SAS can provide data that can enable direct or algorithm-based corrections of the sensor data, as is now routinely done for biogeochemical Argo data in the Southern Ocean [*Williams et al.*, 2016].

These observatories frequently collect data year-round and can provide the seasonal (and longer term) context for the interpretation of the SAS data. SAS, on the other hand can provide the spatial context that they are missing. The combination of mooring and drifter data with the SAS hydrographic section data will for example constitute a very powerful mix for constraining not only the flows of mass, salt, heat and carbon into and out of the AO, but also their variations through time. To ensure that this opportunity is used to its maximum extent, we recommend that relevant moorings are equipped with sensors for seawater CO_2 chemistry and other biogeochemical properties of seawater. Other regions where longer term moored observations are in particular needed to complement the SAS are the Siberian shelves and the Beaufort Sea, which receive most of the discharge from the Eurasian and American continents. Data from moorings will enable better understanding of the large time variations of this discharge, while the SAS will provide information on its spatial imprints.

Autonomous sampling platforms such as gliders and AUVs may also provide greater spatial context to observations conducted from the ships. Some parameters that could be greatly enhanced by such observations include ice algal areal coverage and fish abundances sub-ice from optical methods and plankton patchiness.

Satellite observations

Satellite observations provide large-scale information on sea-ice conditions, surface temperature, chlorophyll *a* concentration, sea surface height and many more properties. The property values are typically derived from the measured radiation data via complex algorithms and SAS will provide information for their ground-truthing. This is in particular important for AO chlorophyll due to the high concentration of CDOM [*Lewis et al.*, 2016] and also the subsurface concentration maxima that develop after the nutrients have been exhausted [*Brown et al.*, 2015]. The SAS will use satellite information as context, for planning, and for upscaling (of surface water pCO_2 observations, for example *Yasunaka et al.* [2016]).

Sediment traps

Investigations of the organic matter sedimentation preferably include sediment traps in different environments. Sites of contrasting biologically activities are in particular interesting, such as high and low production regions, as well as regions with different sea ice conditions. For instance, the role of ice-algae for sinking fluxes can be studied by sediment traps under first year ice.

Process studies

Process studies on how formation and melting of sea ice affect pCO_2 in the water column and consequently air-sea CO_2 fluxes can be carried out using laboratory facilities or coastal area, following for example University of Manitoba group's work and by scientists in Greenland Institute of Natural Resources. However, we still need to understand carbon dynamics under the seasonal cycle of the AO. Single winter cruises can help, but we also need to deploy sensors such as for pCO_2, O_2, fluorescence, etc., tethered to the multiyear ice.

Modelling studies

Although not specifically discussed in this science plan, modelling studies that would be conducted in collaboration with the SAS field efforts can provide longer-term temporal and broader scale spatial context for the observations. In addition, the SAS measurements, although concentrated temporally on the late summer, will provide important validation data to modelling efforts. Particularly for the ecosystem and carbon system measurements, data are scarce from many of the Pan-Arctic regions targeted by the SAS survey plan. This has limited the ability of modellers-observers to validate model performance.

Atmospheric studies

Much of what happens with the upper ocean and the sea ice is impacted by the atmospheric forcing conditions. Even if no atmospheric observation program is directly included in the SAS implementation program much will be gained if some basic observations are performed during the ship sections. These include traditional meteorological measurements, but it would be favourable if also eddy covariance measurements of CO_2 and in shelf regions also CH_4 are performed.

DATA POLICY

The proposed SAS program will follow the successful international GO-SHIP concept that the data collected by the program belong to the community ensuring archiving and open access for anyone requesting it. There will be multiple cruises in multiple regions, yielding a Pan-Arctic perspective linked by an open data policy. Such a policy will maximize the value of the significant international investments. In successful international programs in the other oceans, data policies have been stringent and geared towards rapid, open dissemination, with a clear structure for all data to undergo quality control and to be sent to and available from recognized data centers. Every data set will have a ".doi" assignment so that the data sets can be cited when they are used. To achieve the broadest reach of the data, the policy includes: 1) All Level 1 observations are not proprietary. They are to be made public in preliminary form through specified data centers soon after collection, with final calibrated data ideally provided six months after the cruise, with the exception of those data requiring on-shore analyses. 2). Other data, collected by individually funded programs, may be governed by proprietary data standards, with two years maximum before public release. All data collected as part of the program are to be submitted via a designated data management structure for quality control and dissemination for synthesis. 3) A complete on-line cruise data inventory, applicable to all data collection programs, is to be posted within 60 days of the end of the cruise. All cruise data are to be tracked and linked to their data assembly centers through the project's web site. Ultimately, all data are archived with national data centers or similar recognized repositories, but for ease of user access to data, the project must provide direct links to all project data.

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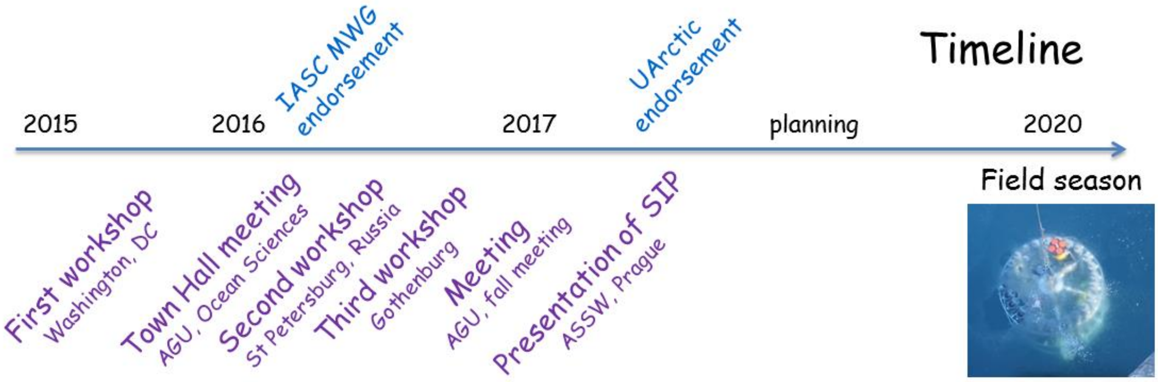
Synoptic Arctic Survey

The motivation of SAS is to answer the question: *What is the present state of the Arctic marine system and what are the major ongoing transformations?* In order to achieve this goal a multiple ship coordinated effort to cover major provinces of the Pan-Arctic system is proposed. In this effort regions that have been sampled only rarely are complemented with those that have been more often sampled, all together in a near-synoptic fashion. The Synoptic Arctic Survey will have three key foci: 1) Physical drivers of importance to the ecosystem and carbon cycle, 2) Ecosystem response and 3) Carbon Cycle and ocean acidification.

The planning of SAS, including the writing of this Science and Implementation Plan is a bottom up initiative among international scientists. Several meetings have been arranged as illustrated by the time line.

SAS has been endorsed by the Marine Working group of the International Arctic Science Committee and the University of the Arctic.




Norwegian embassy, Washington 23-24 June 2015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Univ. Gothenburg, 28-28 September, 2016