Synoptic Arctic Survey

-a pan-Arctic Research Program

Science and Implementation Plan

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BEYOND THE SCOPE OF ANY SINGLE NATION

SYNOPTIC ARCTIC SURVEY (SAS) is a bottom-up, researcher driven initiative that seeks to describe the present state of the Arctic Ocean and understand the major ongoing transformations, with an emphasis on water masses, the ecosystems and 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 the survey should be synoptic across the ocean, which is beyond the scope of any single nation.

Collecting 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 best available technology. This is the target of the SAS, which aims at taking place in 2020 involving coordinated multi-national research vessels in an unprecedented effort to jointly address the Arctic Ocean. This initiative has been endorsed by the International Arctic Science Committee (IASC) marine working group.

THE GOAL is to generate an unmatched dataset that allows for a complete characterization of Arctic Ocean hydrography and circulation, organismal and ecosystem functioning and productivity, and carbon uptake and ocean acidification. Such a comprehensive dataset will also provide a unique reference state, which will allow us to track climate change and its impacts as they unfold in the Arctic over the coming years, decades and centuries. There can be no doubt that not only future generations of polar scientists will benefit from such a reference, but decision makers as well.

There is a historical LEGACY for SAS to build on that 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 exploration, 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.

The vision is that a Synoptic Arctic Survey is performed about every ten years.

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 all too rapidly losing its signature feature as sea ice disappears at an ever-increasing tempo. Not as obvious but equally large changes are taking place beneath the ice/ocean surface where water masses and ocean life interact on different temporal and spatial scales. Together they make up an important and enigmatic mediterranean sea that scientists have been drawn to for centuries, seeking answers that can better explain how the world works and why it changes.

This ongoing transformation of the AO, comprised of roughly half continental shelf and half deep basin and ridge complex, warrants new approaches and new knowledge as it becomes more and more like other oceans, but also because change occurs in all segments of the system, which challenges any given research approach of which there are many examples.

The recently increased seasonal opening of the AO exposes it to more sunlight and wind impact, which alters 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 influences 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 through the Northern Hemisphere Thermohaline Circulation (NHTC); this drives Pacific-origin water (PW) through Bering Strait into the Canada Basin and Atlantic-origin water (AW) through Fram Strait and across the Barents Sea into the Nansen Basin. Thus the AO plays two roles in the global ocean circulation - it provides an oceanic pathway from the Pacific to the Atlantic Ocean; and also 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] and observations suggest these may have occurred without significant change in volume transport [*Beszczynska-Moller,* et al., 2011]. 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 [cf. *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]. These 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].

The interconnections between physical, chemical and (lower trophic) biological changes are slowly beginning to be incorporated into pan-Arctic conceptual models, documenting that such connections exist [*Wassmann et al.*, 2010 and 2015, 2010; *Slagstad et al.*, 2011].

Nevertheless, fundamental questions about Arctic circulation – as basic as water pathways and physical driving mechanisms – remain unanswered at this time. Since Arctic forcing and inflows are changing (with dramatic warming events in Atlantic inflow to the Arctic [*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 deep ocean may be opening [cf. *Kinnard et al.*, 2011] - within a few decades or less the Arctic may see mostly ice-free summers extending fully across its basins.

A warming AO may destabilize glaciers, permafrost, and methane gas hydrates. Changes in temperature, stratification, mixing and chemistry will bring about challenges for Arctic ecosystems, at all levels. Ocean change will also influence sea-ice, 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. Such an understanding will be best achieved by combining observational, theoretical and modeling approaches.

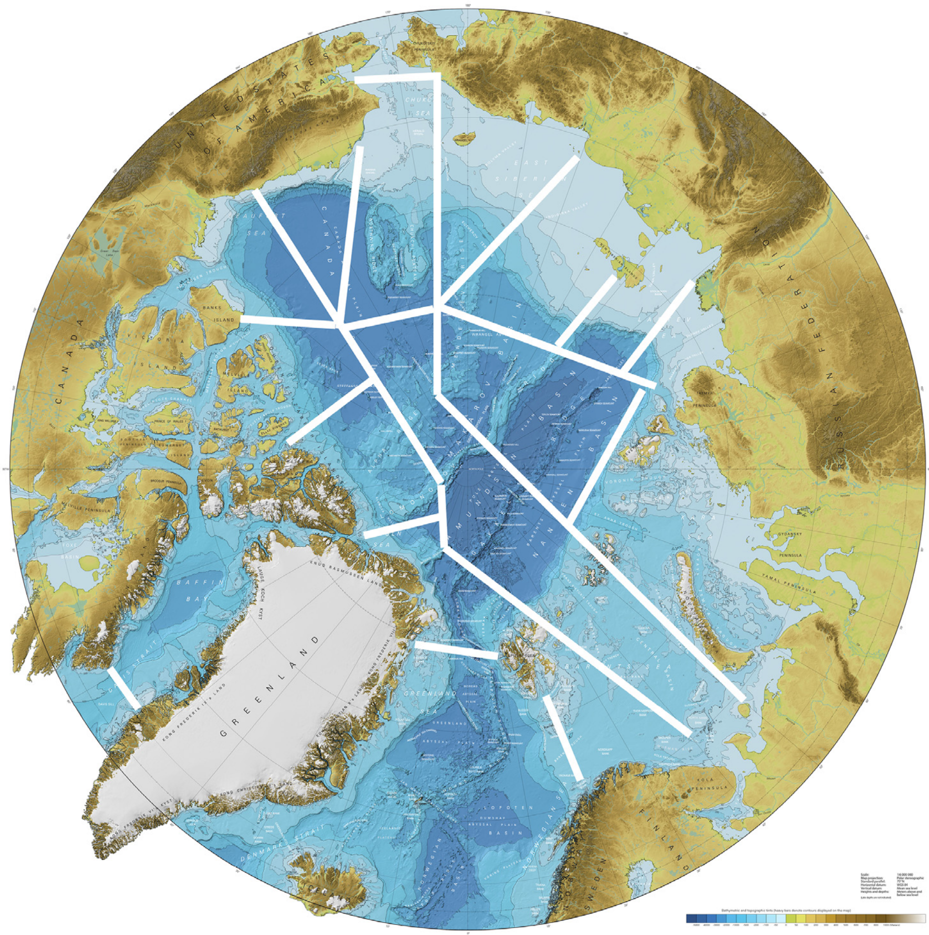
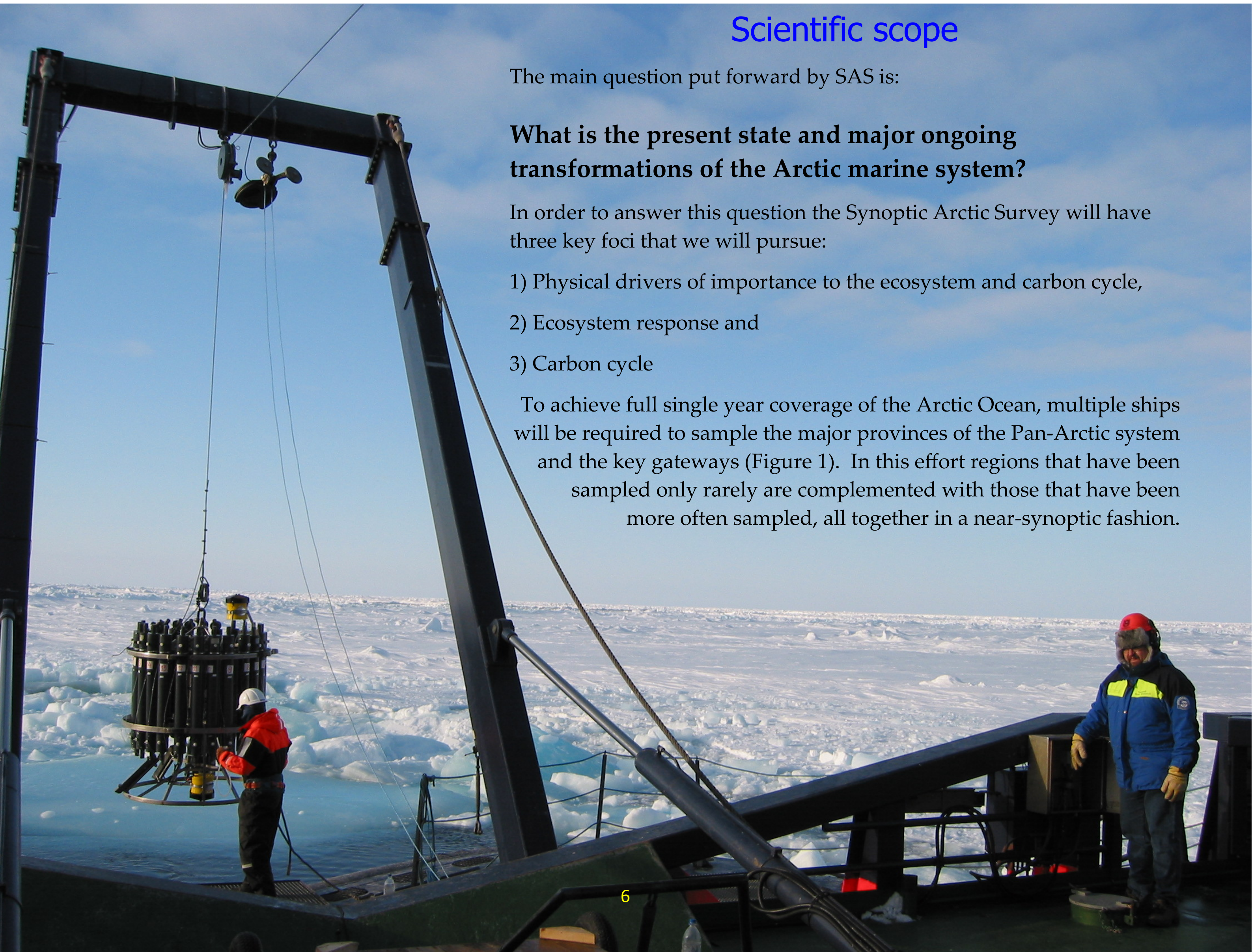


Figure 1. Map with tentative cruise sections for a Synoptic Arctic Survey (base map from Jakobsson et al., 2012)



Scientific scope

The main question put forward by SAS is:

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

In order to answer this question the Synoptic Arctic Survey will have three key foci that we will pursue:

1) Physical drivers of importance to the ecosystem and carbon cycle,

2) Ecosystem response and

3) Carbon cycle

To achieve full single year coverage of the Arctic Ocean, multiple ships will be required to sample the major provinces of the Pan-Arctic system and the key gateways (Figure 1). 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.

A New Arctic Science Frontier

The implementation of SAS as envisioned will provide a unique baseline of the Arctic Ocean 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 present observations, and hence add to the understanding of its dynamics. In fact, the SAS data are a prerequisite for detecting changes of the variable 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 involvement and planning of ice going research vessels from several nations will set the standard for international cooperation and coordination of logistics as well as research procedures. The latter refers to methods applied, technical development as well as training of next generation polar scientists. Hence, the SAS endeavor will form an exceptional long-term legacy for future AO scientists and stakeholders.

A leap forward with the Synoptic Arctic Survey

The Arctic Ocean is an interlinked system 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 as well. In turn, any major perturbation of the carbon cycle will feed back on the climate and the physical domain and further to the ecosystem. The Arctic Ocean is currently changing faster than any ocean on earth. 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.

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 Arctic are expensive and often challenging. Traditionally, the Arctic has not been associated with substantial economic activity – now about to change – which is perhaps why it has not been equally surveyed compare to other oceans. This is, for instance, evident from the World Ocean Circulation Experiment (WOCE).

Still, cruises and traverses have sporadically been carried out by several nations through the years that have produced unique snapshots of how the different biological, physical and chemical systems of the AO behave. 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.

There are good and sound reasons why cruises 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 historically been too demanding in terms of international collaboration or even accessibility. National and international science campaigns actively seeking to explore the connectivity of the carbon cycle with the biological and the physical systems have therefore been few in numbers. This is a serious shortcoming that SAS aims to overcome.

SCIENCE QUESTIONS AND GOALS

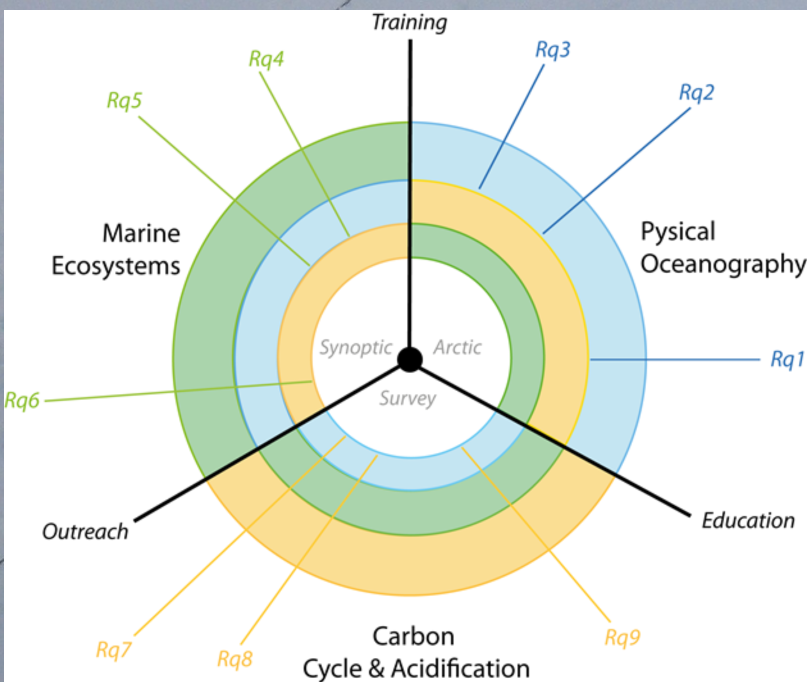


Figure 2. SAS consists of three major themes: (1) Physical Oceanography (in blue), (2) Marine Ecosystems 8 (green), and (3) Carbon cycle and ocean acidification (yellow). Each theme is broken down into three research questions (RQ). The level of complexity increases as one moves counterclockwise

Physical oceanography

Background

The Arctic Ocean is a major player in the global oceanic circulation system through both being a direct link of surface water from the Pacific to the Atlantic Ocean, as well as contributing to deep water formation that constitutes the northern limb of the Atlantic Meridional Overturning Circulation (AMOC). Furthermore 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 of the Atlantic inflow on sea ice loss in the Eurasian Basin has been suggested [*Polyakov et al., 2017*].

Changes in the Arctic Ocean system feed back to the global climate system not only by ocean circulation but also by its effect on the large scale atmospheric flow pattern. For instance has it been suggested that the if the Arctic continues to warm in response to rising 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 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 Arctic Ocean, including the ecosystem and carbon cycle, is the distribution of water masses and their circulation. The Arctic Ocean water column can be considered as a stacking of mostly non-interacting layers, and categorized into typical western Arctic (Canadian Basin) or eastern Arctic (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 Canadian 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 upper layer

by a cold halocline layer [*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 than waters above, and are slightly warmer and saltier in the western Arctic than in the eastern Arctic. 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 provides a "climate handshake" between the Arctic 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. 3).
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 Sea Valley, or continues northeastward as a coastal jet adjacent to Alaska. 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 extent of Pacific water is likely related to the changing position of the Transpolar Drift of sea ice [*Rigor et al.*, 2004] and the Arctic Oscillation [*Thompson and Wallace*, 1998]. Pacific waters exit the Arctic via the Fram Strait and the Canadian Archipelago, their high nutrients fueling ecosystems in the polynyas of the Archipelago [*Tremblay et al.*, 2002]. The Arctic Ocean deep waters, both from the Canadian 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. 3.

Research questions:

RQ1. How are Arctic Ocean water masses and circulation 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?

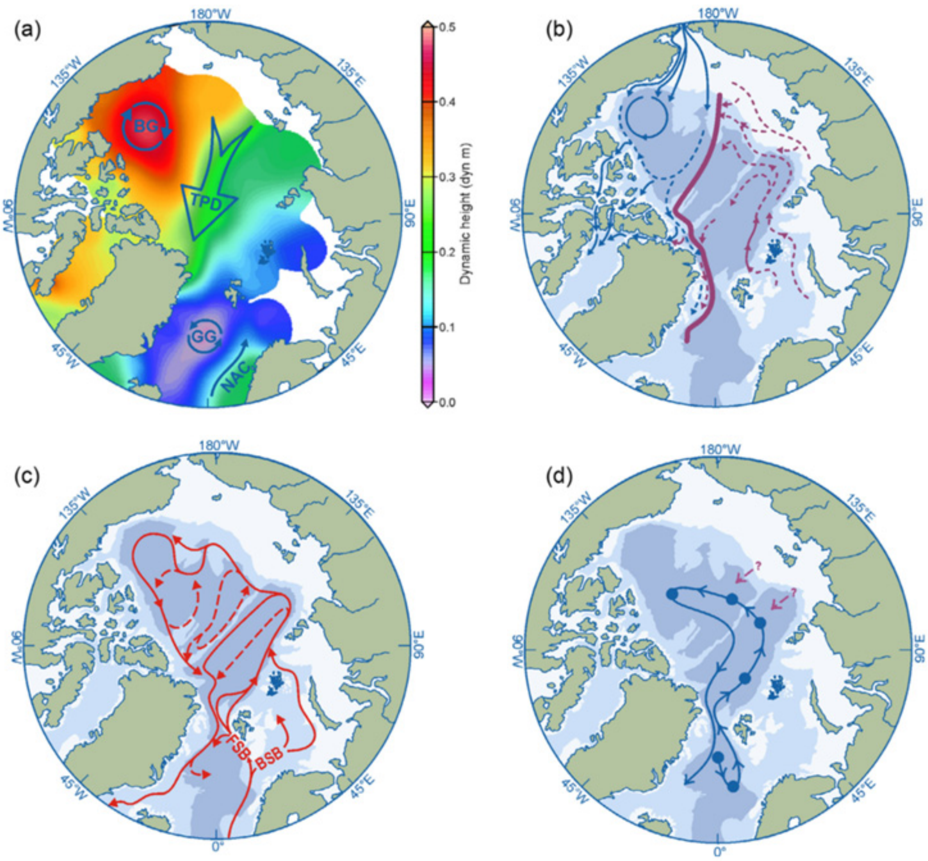


Figure 3. Schematic representations of Arctic Ocean circulation: (a) Surface circulation of the Arctic Ocean as shown by dynamic topography (20/400 dbar) (World Ocean Database 2013), (b) summary of mid-water halocline sources, flows and associated fronts (blue shows Pacific-origin waters, maroon shows 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.]

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

Rationale

The most notable feature of the Arctic Ocean is the perennial sea-ice, which historically has covered about half the Arctic Ocean [*Stroeve et al.*, 2007]. However, in recent decades the perennial sea-ice has been strongly reduced in both extent [*Serreze and Stroeve*, 2015] and thickness [*Kwok and Cunningham*, 2015]. The sea ice, seasonally covering the entire Arctic Ocean, is one key to the remarkable physical quietness of the Arctic Ocean. Sea ice modifies the transfer of wind momentum to the water and dampens surface and internal waves. Furthermore, the ice-freezing process is contributing to the creation of the stacked water column in the Arctic, i.e., the strong layering with cold and relatively fresh waters near the surface and cold and saline waters in the deep, with warmer and more saline Atlantic water in between.

If exposed to the surface, the Atlantic water layer contains sufficient heat to melt the Arctic sea-ice cover. However, due to the low level of subsurface energy to drive vertical mixing, the vertical fluxes in the Arctic Ocean are dominated by slow diffusive mixing through double diffusive intrusions [e.g., *Woodgate et al.*, 2007; *McLaughlin et al.*, 2009], leading to interleaving layers perpendicular to the flow [e.g., *Carmack et al.*, 1998]. Consequently the reduction in sea-ice cover has a profound impact on the processes forming the Arctic Ocean water column, directly through changes to the water mass transformations related to the ice-freezing and melting processes, and indirectly through changes to the wind-induced mixing.

Changes in the sea-ice cover, freshwater sources, and advected water masses will impose changes to the baroclinic circulation from shifts in water mass transformation and distribution. In addition, changing weather patterns, impacted by enhanced vertical heat fluxes from larger areas of open water, will affect the barotropic forcing governing the ocean circulation. Obtaining an anchor point to record the present state of the Arctic Ocean with respect to the discussed parameters, will prove valuable when assessing the rate of ongoing changes, in addition to further enhance our understanding of the Arctic climate system.

Knowledge gaps and goals

While observations in the past have provided a general understanding of the present state of Arctic Ocean water masses and their circulation, much is lacking in the details. The distribution of the upper waters is largely determined by the atmospheric pressure field. As a result, for example, the extent of the Beaufort Gyre is highly variable over decades. Also the front in river runoff from the Siberian shelf seas towards Fram Strait shifts with time [*Anderson et al.*, 2004] Major alteration in sea ice coverage and fresh water content will likely impact the distribution and circulation of the upper waters, as also will changes in the inflow of upper waters from both the Pacific and Atlantic Oceans. However, the specific extent of the impacts is not well known.

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 Arctic Ocean yet exists. The Synoptic Arctic Survey will generate an extensive data set that will:

- Set the reference conditions on a pan-Arctic scale of the water mass distribution during one summer season.
- Enable the assessment of the large scale circulation of intermediate layers from the distribution of water masses during this season.
- Trace changes in the signatures of temperature and salinity in the Atlantic water layer along its flow path within the Arctic Ocean.

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

Rationale

A principal component of the Arctic Ocean heat budget is the inflow of warm Atlantic water. The total northward flow through the Fram Strait is about 7 Sv [*Fahrbach et al.*, 2001], but complex recirculation elements in the strait return approximately half of that immediately to the south [*Rudels et al.*, 2000]. The bulk of the 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 of the Barents Sea and the heat transport to the Arctic Ocean is negligible [*Gammelsrød et al.*, 2009].

About 0.8 Sv of water enters the Arctic Ocean 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.*, 2005a]. The associated heat transport is ~15 TW on average. Approximately 140 TW of oceanic heat enters the Arctic in total, 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 Arctic Ocean varies on timescales from days to decades, related to changes in both in 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 Arctic Ocean almost all physical, biological, and geochemical processes are influenced by the local quantities and geochemical qualities of the freshwater. Freshwater is supplied to the Arctic Ocean by moisture flux convergence above the ocean (~0.06 Sv), adjacent drainage basins (~0.1 Sv), and the last third by low-salinity water 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, and 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. Thus it is 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.

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.

Knowledge gaps and goals

The Arctic Ocean heat budget is governed by the inflow of warm Atlantic water, and a synoptic approach is needed to avoid aliasing by advected anomalies in the budget estimate. However, it has to be considered that using only summer data will lead to aliasing complications due to the salinity and temperature seasonality in the Atlantic Water layer.

The upper layers of the Arctic Ocean are undergoing major increases in the seasonal inventories of freshwater associated with the sea ice freeze and melt cycle, and increased storage within the Beaufort Gyre associated with increased Ekman convergence.

A synoptic approach will:

- Substantially reduce the uncertainty of the heat and freshwater budgets.
- Add to answering the question if the freezing – melting of sea ice result in an increasing or decreasing seasonal fresh water source / sink.

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

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 the subsequent water mass transformations and eventually sinks, leading to potential dynamical shifts in the Arctic Ocean.

The ongoing reduction in the sea-ice cover affects the water mass transformations directly through changes in the amount of brine release and the geographical locations where it occurs, and indirectly through changes to the wind-induced vertical mixing in the upper layer of the Arctic Ocean. 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 Arctic Ocean. While these changes call for extensive process studies, an anchor point in time representing the present state in the Arctic will be vital to determine the rate of change.

The Kara Sea, Laptev Sea, East Siberian Sea and Beaufort Sea 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. Along their southern (continental) boundary the interior shelves are dominated by the major arctic rivers. 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]. Shelf-basin exchange is further modified by shelf-break morphometry (e.g. canyons, valleys, headlands and bottom slope). Brine formation from sea ice production contribute to high salinity bottom water on the shallow shelves [e.g. *Aagaard et al.*, 1981; *Anderson et al.*, 1988] to 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 increased number of deep stations occupied in the Arctic Ocean during the last 20 years combined with the higher accuracy of the measurements has revealed differences between the deep and bottom waters in the separate basins more subtle than just higher temperatures and salinities in the Canadian Basin than in the Eurasian Basin. The exchange of water across the Lomonosov Ridge has been a topic for 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 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.

Knowledge gaps and goals

To better detect regional differences and decadal changes in water mass sources, sinks and transformations, the influence of seasonality and interannual variability must be removed via synoptic data. Assessing the water mass sources, sinks and transformations based on a set of observations carried out over a decade or longer has lead to uncertainties. It is not obvious how to distinguish temporal variability in fronts or water mass distributions from innate spatial variations. A Synoptic Arctic Survey will generate a synchronous data that will contribute to an accurate assessment. While it is tempting to view deep-water properties as close to constant - exchange are slow - small property changes there may signal fundamental transformations of processes not yet fully understood.

Ecosystem Science

Background

The structure of an Arctic Ocean 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 Arctic 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. 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 Arctic [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 Arctic Ocean 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 Arctic 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 Arctic 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 Arctic, 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 Arctic, *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 while the Beaufort, Laptev, and Barents are of much lower biomass. There are only a few studies on high Arctic benthic food webs [reviewed by *Bluhm et al*., 2015; *Kedra et al*., 2015] that 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 Arctic Ocean (CAO) are topics for a developing international agreement for an integrated ecosystem assessment (IEA) 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.

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 carbon flow vary across regional ecosystems of the Arctic?

These ecosystem questions are intricately associated with the physical oceanography of the system, as those characteristics are key drivers of much of the ecosystem structure and functioning, and with the cycling of carbon, as biological processes are key to carbon transformations. The questions are also relevant to the overarching societal challenges faced in the Arctic on both local and global scales. Changes in primary production and carbon cycling could impact the availability of fish or other commercial and subsistence resources in the Arctic. The impacts of increasing human activities on Arctic ecosystems cannot be appropriately assessed or managed without an understanding of the vulnerabilities and regional differences of those ecosystems. Changes in primary production could also modify the uptake or release of CO_2 from surface waters which would feedback to CO_2-driven climate warming.

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

Rationale

Productivity and ice algala and phytoplankton abundance measurements remain sparse for the central Arctic, particularly in recent years that have seen the demise of central Arctic 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 Arctic 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 Arctic [e.g., *Wheeler et al.*, 1996; *Gosselin et al.*, 1997] and transformed the perception of the central Arctic as a biological desert to one that supports substantial 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 Arctic as being of greater productivity than the desert to which it was previously ascribed.

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 Arctic [e.g., *Tremblay et al.*, 2015]. 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 Arctic Ocean 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 Arctic 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 Arctic.

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. 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].

Knowledge gaps and goals

Although multiple lines of evidence show that light availability is increasing in the central Arctic, 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 Arctic Ocean pycnocline, and lateral inputs of nutrients from marginal seas and shelves and the rivers inputs and erosion of those regions. These competing drivers will vary between different Arctic regions. Detecting regional differences and decadal changes in primary production and nutrient availability requires regional comparisons of light availability, primary production, nutrient concentrations, hydrographic structure, and circulation on pan-Arctic scales and at synoptic time frames to remove the influence of seasonality on the regional 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?

Rationale

Both eastern and western Arctic ecosystems can be impacted by the northwards range expansion of subarctic species that either migrate north into Arctic marginal seas and basins following recent warming of Arctic water masses, that are carried north in the prevailing circulation, or that are carried into the Arctic 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 subarctic 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 Arctic [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 Arctic 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 Arctic after being advected there in the prevailing currents. These include the subarctic species *C. finmarchicus* in the eastern Arctic and subarctic *Neocalanus* spp. and temperate *Eucalanus bungii bungii* in the western Arctic [e.g., *Ashjian et al.*, 2003; *Kosobokova and Hirche*, 2009; *Kosobokova and Hopcroft*, 2010]. In the western Arctic, distinct genetically differentiated populations of C. glacialis have been observed in the Bering/Chukchi Seas vs. the Central Arctic [e.g., *Nelson et al.*, 2009]. Although sometimes observed in high abundance in the central Arctic (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, 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 Arctic in many previous studies, it appears that their occurrence may be observed further to the north and at higher abundances than previously observed [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. 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]. The question of whether ecosystems in the Arctic can sustain such populations over the winter is of interest to both Arctic and non-Arctic nations.

Knowledge gaps and goals

Understanding of the potential establishment of expatriate species in the Arctic 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 Arctic environment. Multiple approaches are required to achieve this understanding, including field sampling of multiple trophic levels, including the benthos that is supplied with planktonic larvae, identification of pathways of immigration through association of species presence and abundances with ocean currents, experimentation to determine species tolerances to Arctic environmental conditions, description of species' phenologies and synchronization with production and prey species cycles, and multiple modeling approaches. Advances in understanding that can be achieved through the SAS include field sampling of multiple trophic levels to identify expatriates, associations of those expatriates with different water masses and water pathways, and pan-Arctic comparisons to assess the relative vulnerability of different Arctic regions to ecosystem shifts resulting from expatriate colonization.

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

Rationale

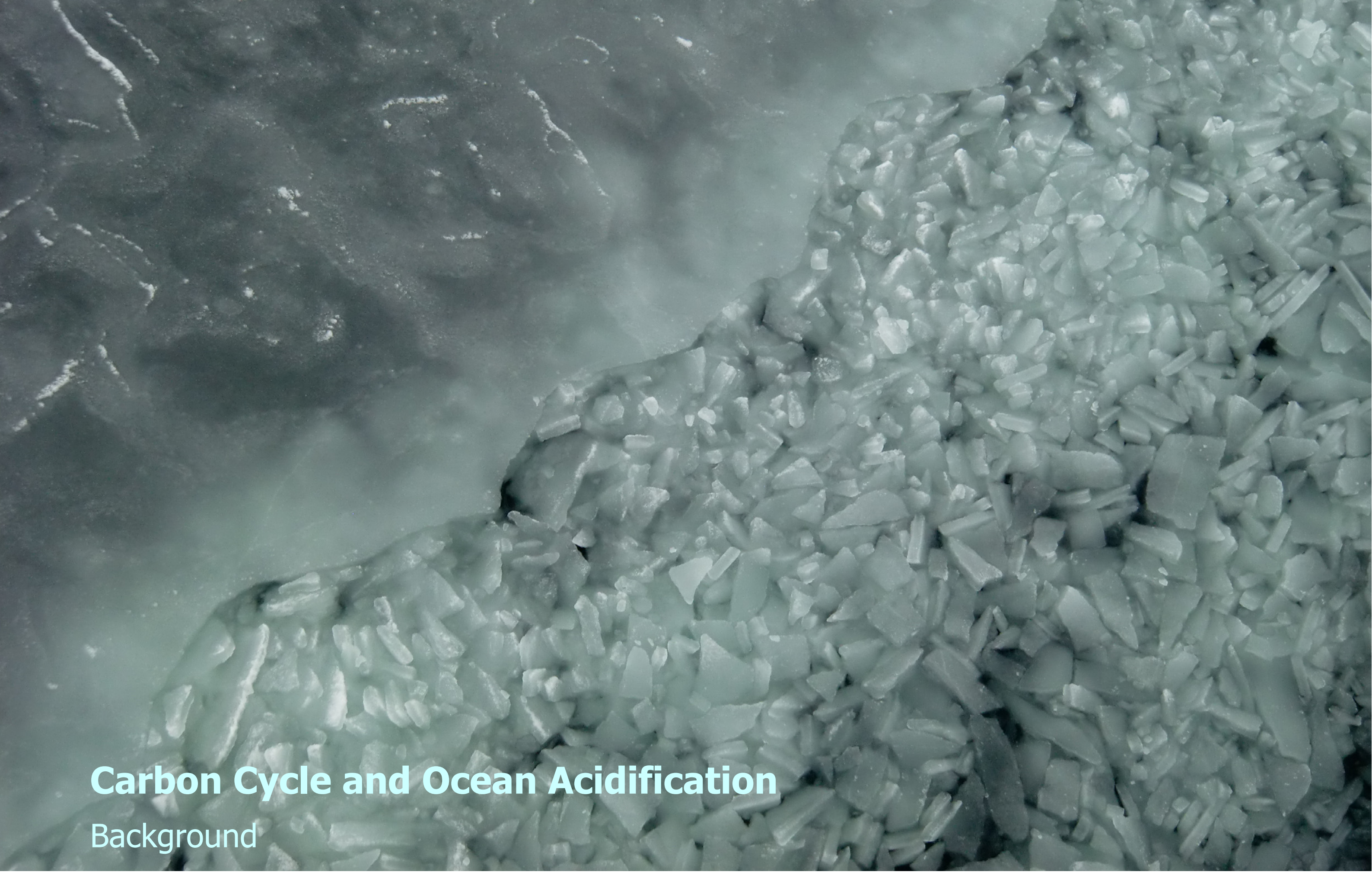
As physical drivers change, species and size composition of pelagic and benthic communities, dominant species, and the relative number of different trophic levels may be modified, thus altering the flux of carbon through the ecosystem and the availability of prey for upper trophic levels such as fish, seabirds, and marine mammals. Ecosystem structure, including carbon pools and transformations, are undersampled and poorly defined for the central Arctic with very little work done on some of the trophic levels (e.g., bacteria, viral predators, microzooplankton) that may have significant roles in carbon flow. Because the modification of environmental drivers by climate change differs between Arctic regions, variation in the impacts of 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)

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 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 Arctic are relatively unknown, including the fate of export fluxes over the slope into the deep Arctic Ocean [*Kedra et al*., 2015].

Knowledge gaps and goals

Although significant work has been done in marginal seas and shelf systems, understanding of central Arctic standing stocks and species compositions for all ecosystem components is much less well defined. Furthermore, few carbon transformation rates are available for most central Arctic regions, making constraining ecosystem carbon budgets very difficult. The responses of Arctic organisms to changing temperature conditions also are very poorly understood. Quantification of the 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. Specific measurements could 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
- Carbon transformations including respiration, production, consumption, and regeneration



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], this is far above the stabilization required for reaching the 2-degree target, of between 430-480 ppm (66% probability for staying within 2 degrees of warming).

The absorption of man made CO_2 by the ocean is driven by the increased CO_2 concentration in the atmosphere from fossil fuel burning, cement production and land use change. Ocean overturning is essential to maintain this large oceanic CO_2 sink. Firstly, it brings old water that has not been exposed to present atmospheric CO_2 levels to the surface ocean, these have capacity for absorbing anthropogenic CO_2. Secondly, ocean overturning brings surface waters that have absorbed anthropogenic CO_2 to the deep ocean, where it is stored in the large volume of the abyss. The 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, see oceanography section.

Climate change may not only decrease ocean uptake of anthropogenic CO_2, it may also mobilize the large reservoirs of natural carbon in the ocean (Table 1). Even a small relative perturbation of these natural ocean reservoirs can lead to massive outgassing or ingassing significantly affecting the atmospheric reservoir and CO_2 concentration. For example the regular occurrence of ice-ages of 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). In the atmosphere carbon exists primarily in the form of CO_2, while in the ocean it exists in the form 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 current net uptake of fossil fuel CO_2 affects ocean chemistry and leads to ocean acidification, which may seriously affect marine ecosystems. In short, in seawater CO_2 exists as dissolved inorganic carbon, this is carbonic acid (H_2CO_3), bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}), the two latter are bases while the first (H_2CO_3) is an acid. 19 out of every 20 CO_2 molecules that now enter the ocean react with the strongest base (carbonate ion) to make bicarbonate ion.

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

The net effect is to lower the concentration of carbonate ions and decreasing the pH as CO_3^{2-} is a stronger base than HCO_3^- and in addition 1/20 CO_2 molecules is hydrolysed to carbonic acid. This ocean acidification has been shown to have detrimental effects on many forms of marine life. For example, neurotransmission is affected and 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. Also, the loss of carbonate ions threatens calcifying organisms such as corals, *coccolithophorides* and *pteropoda*. As ocean acidification aggravates the energy cost of calcification increases and it becomes harder to maintain reef or shell structures, in the worst case they may simply start to dissolve. Sensitivity to and extent of ocean acidification is a decisive factor for future marine ecosystem structure, production and harvestability and magnitude and impacts need to be quantified.

The Arctic Ocean plays a key role for the partitioning of carbon between the upper and deep ocean. It is also in particular sensitive for ocean acidification. The production of Arctic deep waters not only transports anthropogenic carbon 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 Arctic Ocean will be one of the main conduits for this carbon into the atmosphere-ocean system.

The strong sensitivity of the Arctic Ocean for ocean acidification is a consequence 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 Eq. (1) 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. Finally, the low concentrations of carbonate ions means that the

carbonate buffer capacity is low, hence this is one of the regions where we will see the greatest pH change as a consequence of ocean acidification.

On this background we identity three research questions are in particular pertinent to resolve, not only for Arctic Ocean but also global science and policy development:

Research questions:

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

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

RQ9: What is 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 low temperatures and the ice-cover of the Arctic Ocean are what provide it with special significance for the global carbon cycle. The warming and loss of sea ice are what provides it with special sensitivity to climate change.

Rationale

Arctic sea ice forms in numerous polynyas along the Arctic continental margins [*Tamura and Ohshima*, 2011]. The resulting brine formation is an efficient way to transport 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 keep taking 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, such 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].

The established 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 Arctic 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, and due to CO_2 uptake by primary production in the "inflow-shelves" [*Carmack and Wassmann*, 2006].

The sea-ice cover also limits primary- and, consequently, export production in the deep basins of the Arctic Ocean. Thick ice and its snow cover acts as an efficient barrier for sunlight, required for photosynthesis, to the upper ocean. In addition, it insulates the ocean from the extreme winter heat loss and limits 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 Arctic

Ocean 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 'inflow-shelves' [*Carmack and Wassmann*, 2006], which are receiving nutrient rich water from the Atlantic and Pacific Oceans. As a result these two areas host some of the most productive ecosystems of the global oceans. In contrast, primary production on the interior-shelves and outflow-shelves relies on upwelling of nutrient rich arctic boundary currents,

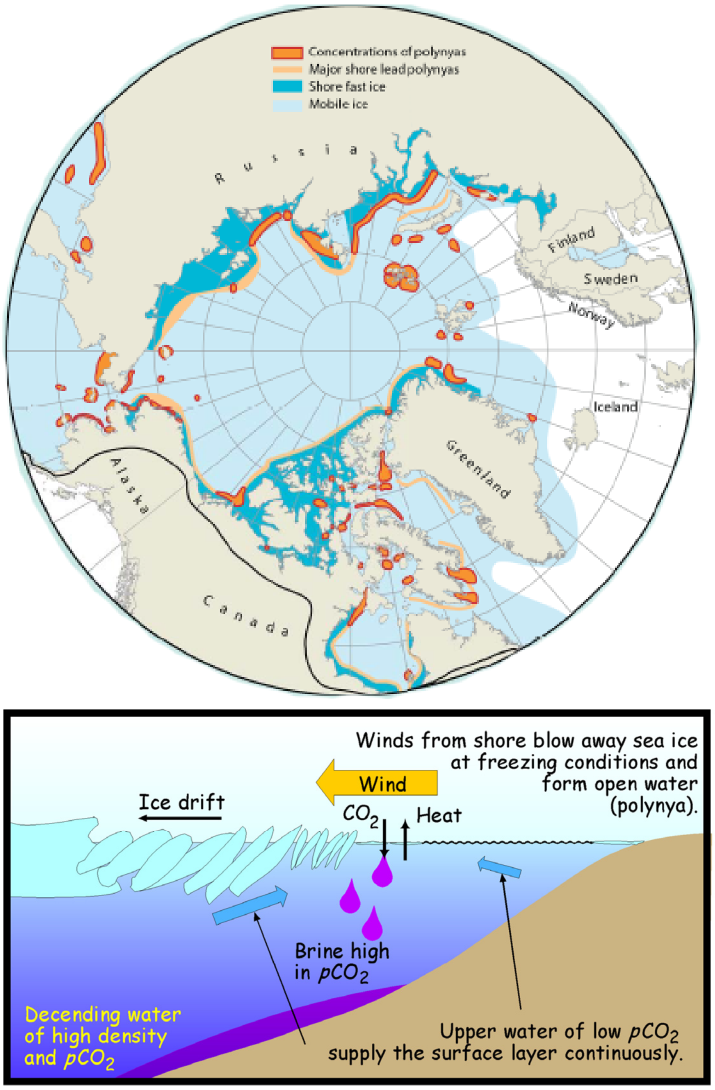


Figure 5. Distribution of known polynyas [*Meltofte*, 2013] and schematic of ice, brine and carbon export processes in polynays.

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 sea-ice have taken place, with regard to both thickness and extent. 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 aggravate with climate change, but the winter-ice is likely more resilient, at least in the central part of the Arctic Ocean. As a net result, a seasonally ice covered Arctic is expected in the future warmer climate. In this situation brine production will change, 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. Combined this will change the contribution of the Arctic Ocean to maintaining the global ocean

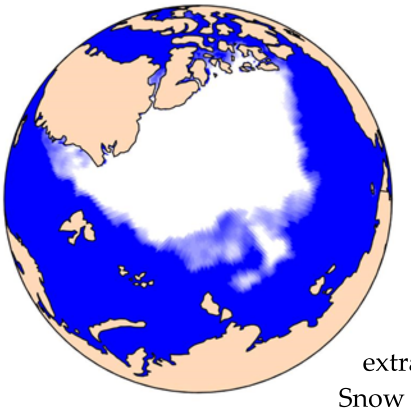


Figure 6. Arctic sea ice concentration September 2012, extracted from National Snow and Ice Data Centre

carbon dioxide reservoir and uptake. In order to understand the potential implications on ocean carbon storage the present state and driving processes must be accurately quantified and identified; i.e. the magnitude and components of the Arctic Ocean carbon budget must be quantified.

Knowledge gaps and goals

While estimates of large scale Arctic carbon uptake and physical and biological transformations and transports exist, they have unacceptably large uncertainties. *Olsen et al.* [2015] synthesised published estimates 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). For the present state a closed budget is not achieved, 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.

The Synoptic Arctic Survey will generate extensive and synchronous data to enable carbon budgeting with unprecedented accuracy and resolution, allowing quantified assessments of carbon transports, transformation and storage at regional scales as well as at biological and physical process level to determine:

- The import of carbon from horizontal advection, air-sea fluxes and (from RQ8) riverine transports.
- The net vertical transports of carbon to the intermediate and deep ocean associated with dense water (e.g. brine) production and biological matter and export production.
- The horizontal exports of carbon to the surrounding ocean areas.
- Altogether quantifying the role of the AO for sustaining the ocean reservoir and for uptake of natural and anthropogenic carbon, and its sensitivity to climate change.

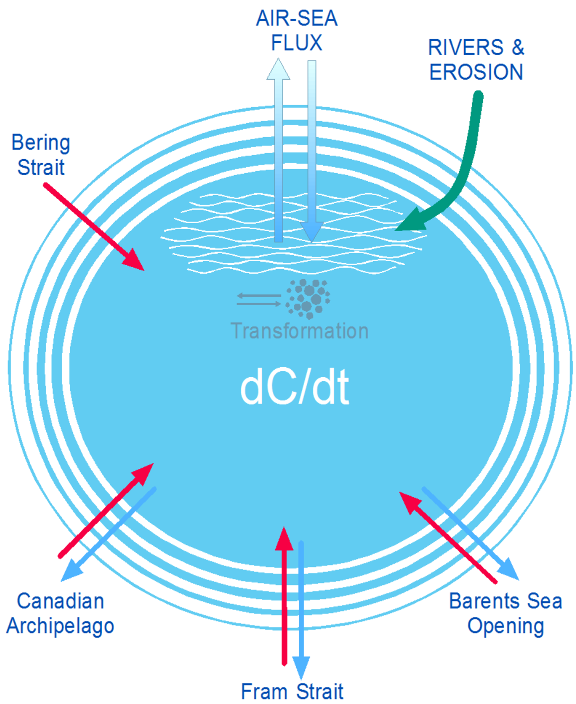


Figure 7. Schematic illustration of the Arctic Ocean carbon budget, including the exchange with surrounding oceans, atmosphere and land (rivers and erosion), as well as the biogeochemical transformation and storage (dC/dt) term. (Figure after *Olsen et al*, 2015.)

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 is the input and fate of terrestrial and subsea carbon to the Arctic Ocean?

Global warming may mobilize organic carbon now stored in the terrestrial and subsea permafrost zones surrounding the Arctic Ocean. Additionally, large pools of fossil methane exist on the seabed in the shelf seas. This represent a very strong potential global warming feedback and the Arctic Ocean 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 contains only about 1% of the world ocean's volume. The drainage basin (~24×10^6 km^2) of the rivers entering the AO is twice as large as the AO itself, and includes large permafrost regions (Fig. 8). Already today the rivers add large amounts of terrestrial organic carbon to the Arctic shelf seas as a result of summertime thaw. Additionally, reduced sea-ice cover increases coastal erosion as a result of high seas during storm events before the sea ice forms in the autumn, this input of organic carbon can be of the same order of magnitude as that added by rivers [*Stein and Macdonald*, 2004].

The organic carbon is delivered in the forms of Dissolved Organic Carbon (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, Other fractions persist long enough to be entrained into subsurface halocline waters in conjunction with ice formation and brine rejection. Eventually much of these are exported to the Atlantic and global oceans and mineralised 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.

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

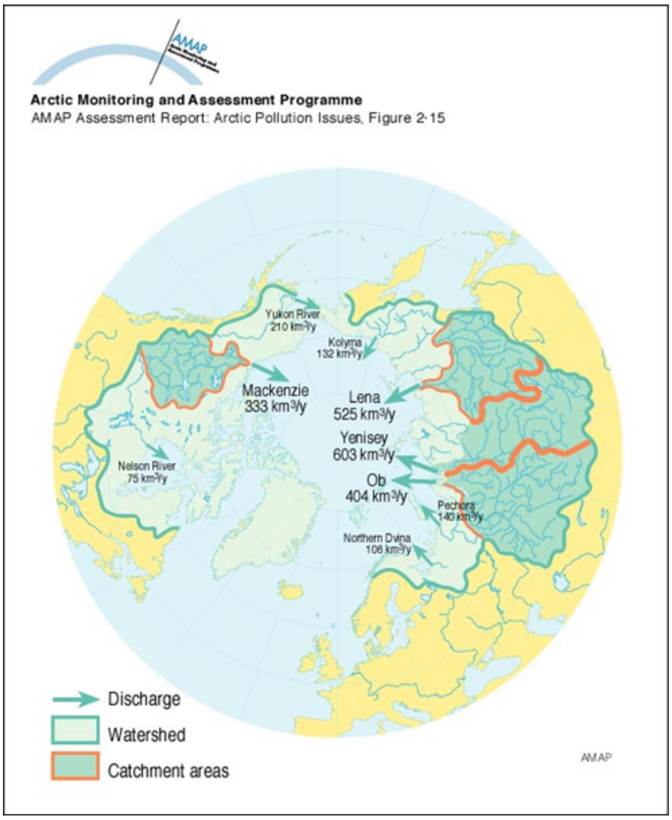


Figure 8. Arctic Ocean watershed and Catchment areas of the largest rivers and annual runoff (km^3 yr^{-1}) [*AMAP*, 1998]

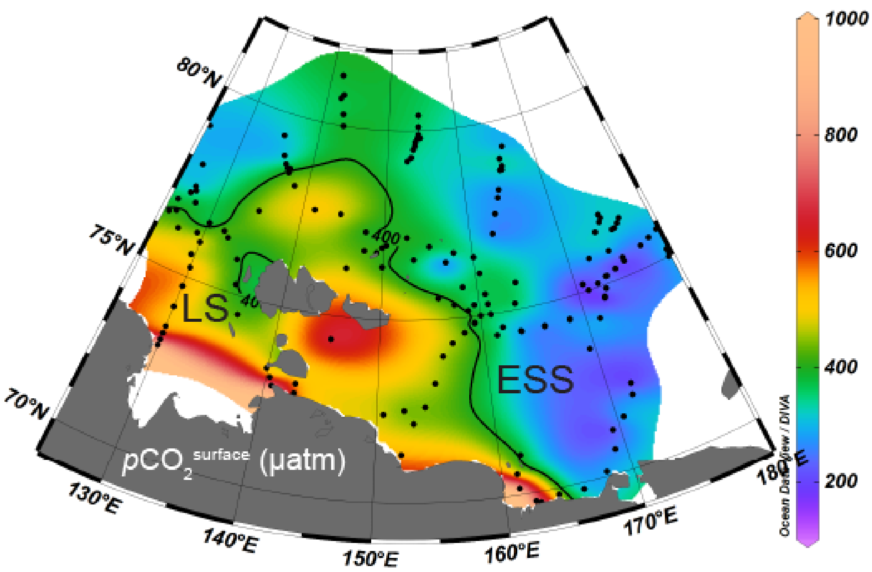


Figure 9. pCO_2 in the surface waters of the Laptev Sea (LS) and East Siberian Sea (ESS) as observed in 2008 and 2014. The isoline of 400 µatm indicates the atmospheric level.

Large quantities of the potent greenhouse gas methane are trapped in the subsea permafrost on the Arctic Shelves. It has been estimated that about 540 Gt of methane is trapped in the form of chlarates (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). It 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]. 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 aggravate. Combined with the expected increase in precipitation, a significant amount of the mobilized organic carbon will be transported with the rivers to the Arctic shelf seas. Further additional organic carbon input will come from enhanced coastal erosion [*Stein and Macdonald*, 2004]. Release of the 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 Arctic Ocean release rates must quantified as well as the factors governing their further degradation to CO_2.

Knowledge Gaps and Goals

Widespread imprint of terrestrial organic carbon has been documented in both Laptev Sea, the East Siberian Sea and off their shelf breaks (Fig C5), [*Anderson et al.*, 2009; *Anderson et al.*, 2016]. Pan-Arctic coverage is now needed to assess basin-wide impacts and generate a baseline that allows robust detection of any changes in the future. In addition to the spreading, oxidation rates of the various organic compounds and any relation to environmental variables (such as temperature) must be determined.

Outgassing of methane has also been documented through recent field work [e.g. *Shakova et al.*, 2014; *Thornton et al.*, 2016]. However, while the measurements that have been carried out certainly agree that methane outgassing is larger in the ESSAS 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 CH_4 flux measurements More information on the spatial variability of methane outgassing and its stability in the water column is needed for a reconciled estimate.

The Synoptic Arctic Survey will generate a comprehensive pan-Arctic data set of carbon in its various inorganic and organic forms, and isotopic signatures. Combined with nutrients, oxygen and age tracer data this will allow determination of:

- The present supply of terrestrial carbon to the different regions of the Arctic Ocean and delineation of the various forms and sources.
- The factors that control the fate of terrestrial DOC and POC and their oxidation to CO_2 in the water column.
- The amount of CH_4 released at the seafloor, the fraction escaping to the atmosphere and the factors that determine the rate of oxidation in the water column.

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 Arctic. Within the next few decades the remainder will follow suit with potentially serious impacts on marine organisms. Yet, the actual ecosystem impacts are still virtually unknown.

Rationale

The Arctic ecosystems are uniquely adapted to the cold, hostile and seasonally highly variable conditions that have prevailed for the past millions of years. Human induced change is 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, which is a consequence of the absorption of anthropogenic CO_2 is of particular concern given the low buffer capacity of the Arctic Ocean's inorganic carbonate chemistry. In this region the concentration of carbonate ions is low and the calcium carbonate saturation is in particular sensitive to additional CO_2 absorption. Aragonite undersaturation has already been observed in some regions of the Arctic [*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 or reef structures (i.e. corals). Undersaturation is a critical threshold for them as they are significantly stressed and may actually dissolve when it occurs. The situation is further aggravated by the expected increased precipitation and run off, and more widespread seasonal ice melt. This adds low buffer capacity freshwater to the system. The terrestrial run off also add organic carbon, as discussed above, a fraction which is oxidised to CO_2 and increasing 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 sensory abilities and behavior of many marine species, including fish, with potential effects on predator-prey relationships. In a recent study, reduced survival of Barents Sea cod larva was observed to decline under increasing OA [*Stiasny et al.*, 2016]; mortality doubles when exposed to ocean acidification 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 Arctic, warming and disappearance of the perennial sea ice is of particular relevance, with their impact on biogeography, light access and 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 Arctic Ocean. Finally, increases in shipping and extraction of natural resources leads to a higher risk of pollution.

Knowledge Gaps and Goals

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 Artic. Sea-ice meltback, 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 as observed in OA 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.

The observing strategy of the Synoptic Arctic Survey will allow significant advances on these issues. The simultaneous collection of hydrographic, chemical and ecosystem data will enable:

- The assessment of the Arctic Ocean's carbon budget and its likely future change (RQ1) including the amplifying effects of terrestrial and subsea carbon sources (RQ2).
- Delineation of current environmental boundary conditions for the various ecosystems.
- Reveal tolerance limits by sampling in areas with naturally low pH.
- Better design of perturbation experiments.
- Better understanding of "all" processes relevant for impacting OA, establishing the basis for model projections of future environmental conditions.

IMPLEMENTATION

Throughout much of the 20th century the AO – and its central deep basins in particular – was viewed as a small, remote, slowly changing and relatively unimportant part of the global system. Now, however, recent, historically unprecedented changes in the Arctic environment are driving a need to "catch-up for lost time", and this includes obtaining data which will greatly reduce ambiguity in achieving a pan-Arctic perspective. Improving understanding of the full scope and impacts of Arctic change requires temporal knowledge of the dynamical features of the AO, its heat, salt, and carbon budgets, and its large-scale marine ecosystems, each of which must be observed in appropriate locations and intervals. Observing systems designed to address these questions in the mid- and low -latitude oceans typically consist of three components: (1) Lagrangian drifters and floats, e.g., global ARGO array (2) Eulerian measurements at key mooring sites such as straits or well defined boundary currents, and (3) repeat hydrographic/carbon/tracer sections which resolve the principal features of the water masses and circulation and their changes.

In the AO various Lagrangian approaches are either implemented or are considered. We foresee that this technique will play an important role in SAS, but do not detail implementation in this plan. Eulerian measurements are today at place, e.g., in the Fram Strait, the Bering Strait, and the Davis Strait, and SAS field phases will contribute to continuation and potential expansion of those efforts.

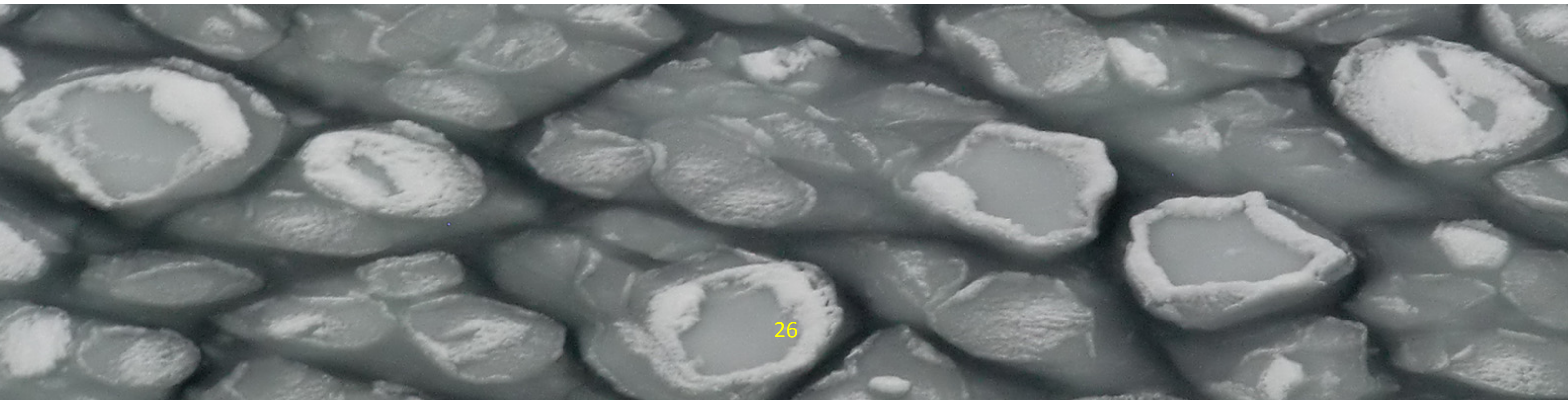
In this plan the focus is on carrying out a synoptic set of sections, as the present AO CTD/hydrographic/carbon/tracer database does not permit ready study of key issues related to regional and global ocean change research. The principal limiting issue with the present data, except perhaps in deep waters below sill depths, is significant convolution of spatial and temporal variability. A second critical problem is uneven data quality for most variables other than temperature and salinity. The measurement protocols of the large international programs in the other oceans have not always been followed in Arctic Ocean work. For purposes of measurements unrelated to process studies, ice cover is less of a challenge today for summer operations than previously, except for areas immediately north of Greenland and the Canadian Archipelago and, intermittently, in some portions of the Trans-Polar Drift. Thus we see much lower logistic constraints to the suggested plan, compared to the past, even with some adjustments of the intended cruise tracks during execution.

Under optimum conditions all three foci - physical oceanography, ecosystem, and biogeochemistry - can be fitted on all ships and with common sampling and analytical techniques. Because the capabilities of vessels and groups vary there might be a need to take different approaches and hence the implementation strategy follows the GO-SHIP protocol for ship based measurements, i.e. their Level-1 to 3 prioritization. All ships should however record underway navigation/

Physical oceanography

The positioning of the sections are based on crossing the general oceanic currents and flow paths as we know them from historic investigations, and to fit in with historic sections when suitable. The station spacing preferentially should resolve the Rossby radius and thus must not exceed 20 nm. Over ridges and at shelf slopes where boundary currents are present, even closer spacing might be favorable. The CTD package should also include an oxygen sensor and preferable also one for transmission or fluorescence, as well as be equipped with an ADCP. For the calibration of the sensors, water for determination of salinity and oxygen should be taken and analyzed on board shortly after sampling according to the best practice. In the strongly stratified surface water it is essential to determine salinity in the water samples in order to get a representative value for the other parameters determined.

The CTD sensors should be calibrated before the cruise and favorable also after. The signal processing should follow the best practice in order to avoid errors at the same time as the depth resolution is kept to its best. It is strongly suggesting that international GO-SHIP protocols



Ecosystem Science

Addressing these questions requires quantifying the different carbon stocks and the species composition, dominance, and size structure in pelagic and benthic trophic levels and ecosystem compartments and establishing trophic linkages and carbon flows through experiments that quantify carbon transformations between trophic levels (e.g., primary production, grazing, carbon export flux). 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 Arctic carbon cycle.

Table 3. Ecosystem parameters and methodology for sampling. Each parameter will require specific analyses following sample or data collection that are not specified here.

Parameter	Methodology
Viruses	Niskins
Bacteria (Water Column, Benthic)	Niskins, Box Core or Multicore or other corers
Phytoplankton	Niskins
Microzooplanton	Niskins
Meso- and Macro- zooplankton	Bongo nets, Multinet, Optical Insturments, Acoustics
Benthic Meio- and Macro- fauna	Box Core or Multicore or other corers
Benthic Epifauna	Benthic Camera, Beam trawl
Epontic Communities	Under-ice imaging, ice cores, sub-ice sampling
Ichthyoplankton	Aluette or Tucker Trawls, Acoustics
Fish*	Trawls, Acoustics
Seabirds	Visual observations
Marine Mammals	Passive acoustics, visual observations
Production from O_2-Ar,O_2 isotopes	Niskins
Primary Production	Niskins, On-Deck Incubations using Isotopes
Other Key Carbon Transformations	Niskins, Nets, Corers, Incubations

*Only in shelf/slope regions

Table 4. Sampling frequency for ecosystem parameters.

	Bottom Depth Range (m)	Station Frequency
Water Column Sampling	All	Every Other CTD Station
Benthic Sampling	25-200	Every 50 m of bottom depth
	200-500 m	Every 100 m of bottom depth
	500-1000	500 and 1000 m
	> 1000	TBD

Carbon Cycle and Ocean Acidification

Implementation C-system

The Synoptic Survey of the Arctic will be conducted by many scientists from various laboratories, hence it is important to have well understood protocols in place for measurements. We apply the GO-SHIP protocol for ship based measurements and suggest its Level-1 measurements with some modification relevant to AO conditions (Table 5). Added to these are sensors for surface underway system, primarily T, S, pH and pCO_2.

Sampling and analysis of the inorganic carbon chemistry should ideally be carried out at all CTD stations. However, some flexibility can be allowed in order to enable sample analysis to keep up with collection. For example, sampling of water at every second CTD station may be adequate. The depth resolution should be high in the upper waters where the variability is largest. In the deep and bottom waters larger depth spacing is sufficient, apart for very close to the bottom, where high resolution should be in order to observe any chemical gradients caused by organic matter decay. Suggested sampling depths are provided in Table 6.

(1) Impact by ice conditions on carbon fluxes

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 Univ. 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 central Arctic Ocean. Single winter cruises can help, but we also need to deploy sensors such as pCO_2, O_2, fluorescence, etc, tethered to the multiyear ice.

(2) Terrestrial carbon input to the Arctic Ocean

In times of substantial permafrost thawing there is a need to investigate the input of carbon to the Arctic Ocean from land over a longer time frame. However, given the variable discharge from both the Eurasian and American continents a one-time survey is not fit for this purpose. Hence, it would be preferable to establish time series in Siberian Shelves as well as in the Beaufort Sea to obtain the basin scale fluxes. These time series should include CDOM measurements from ships as well as satellite measurements.

(3) Biological uptake and settling of carbon

Investigations of the organic matter sedimentation preferably include sediment traps in different environments. These include sites of contrasting biologically activities, low and high production regions, as well as under different sea ice conditions. For instance, the role of ice algae in sedimentation can be studied by sediment traps under first year sea ice.

(4) Advective transport of carbon

There are several projects addressing the transport of water through the different passages to the Arctic Ocean, including the T & S properties. For instance there is a long time mooring array in Fram Strait, as well as in parts of the Bering Strait. Preferable these moorings, and others of relevance, should be equipped with sensors for C-system parameters. Sensors are under development and at the time of SAS they might be suitable for a full annual cycle.

Table 5. Level 1 parameters to be determined on all cruis-

Parameter	Note
Bottle salinity	
Nutrients (NO_3/NO_2, PO_4, SiO_3)	
Dissolved oxygen (O_2)	
CFCs and SF_6	
Dissolved Inorganic Carbon (DIC)[1]	[1] At least two of these parameters
Total Alkalinity (TAlk)[1]	
pH[1]	
$\partial^{13}C$ of DIC	
$\partial^{18}O$ of H_2O	
Methane (CH_4)[2]	[2] On the shelves and at the boundaries
Dissolved organic carbon (DOC and CDOM)[3]	[3] Focus on the upper waters

Table 6. Suggested depths of water sampling.

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

Seasonal implications

Most present AO observations are from summer time only and with limited regional distribution. Given the heterogeneous conditions of the Arctic, with variable sea-ice cover and contrasting hydrographic domain, combined with large temporal variations, carefully planned and executed large scale observations are required to characterize the system with adequate detail. Coordinated pan-Arctic surveys for mapping will provide a comprehensive reference point to detect future changes and information to evaluate model simulations. Application of physical, biological, and chemical sensors on floating or moored platforms and autonomous vehicles as well as satellite-based observations will be especially useful to increase space and time coverage of shipboard observations.

Implementation summary

The Synoptic Arctic Survey will provide a comprehensive reference point to detect future changes as well as information to evaluate model simulations. The sections included in the SAS can be occupied during the annual sea ice minimum. To obtain full value from the data it is important that the sections follow the same procedures and standards as those from the global repeat hydro/tracer/carbon program.

The Synoptic Arctic Survey will rely on complete data interoperability. Hence sampling plans for all cruises involved in the survey require vertical profiles that will include international GO-SHIP Level 1 and 2 parameters and their attendant data quality and documentation requirements. Data management is an important aspect of the program, and the groups which handle GO-SHIP data - such as the CLIVAR and Carbon Hydrographic Data Office (CCHDO) - are prepared to handle data management tasks, and at no direct cost to the Arctic program.

DATA POLICY

The proposed SAS program follows the successful international GO-SHIP concept that its data belong to the community. There will be multiple cruises in multiple regions, hence a trans-Arctic perspective can be gained only by an open data policy. Such a policy will maximize the reach of the significant international investments which would be made. 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 and 2 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 (see Table 1). 2). Level III 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.

A project Oversight Committee, consisting of a subset of program PIs plus members of the community at large, makes recommendations on changes in lines, measurements, measurement teams, and entrainment of new scientists. They advocate adequate and consistent coverage of all Level 1 and 2 observations. They work to ensure smooth interactions with national agencies and individual investigators (Level 3), and that adequate support is provided for data management. They serve as contact for coordinating with relevant international scientific groups such as GO-SHIP and IOCCP, and coordinate with appropriate international steering committees. They will oversee pre-cruise planning, data submission, and documentation.

REFERENCES

Aagaard, K., Coachman, L. K., and Carmack, E., (1981), On the halocline of the Arctic Ocean. Deep- Sea Res., Part A, 28, 529-545.

Aagaard, K., Swift, J.H., and Carmack, E.C., (1985), Thermohaline circulation in the Arctic mediterranean seas. J. Geophys. Res., 90, 4833-4846.

Aagaard, K., and Carmack, E. C., (1989), The role of sea ice and other fresh water in the Arctic circulation. J. Geophys. Res., 94, 14485-14498.

ACIA. (2005), Arctic climate impact assessment scientific report, Cambridge University Press, Cambridge, UK.

Aksenov, Y. et al., (2011), The Arctic Circumpolar Boundary Current. J. Geophys. Res., 116, C09017, doi:10.1029/2010JC006637

AMAP (1998), AMAP assessment report: Arctic pollution issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xxii+859 pp.

Anderson, L.G., et al., (1988), Nutrient regeneration in cold, high salinity bottom water of the Arctic shelves. Cont. Shelf Res., 8 1345-1355.

Anderson, L.G., et al., (2004a), Enhanced uptake of atmospheric CO_2 during freezing of seawater: a field study in Storfjorden, Svalbard, J. Geophys. Res., 109, C06004, doi:10.1029/2003JC002120.

Anderson, L.G., et al., (2004b), Variability in river runoff distribution in the Eurasian Basin of the Arctic Ocean. J. Geophys. Res., 109, C01016, doi:10.1029/2003JC001773.

Anderson, L.G., et al., (2011), East Siberian Sea, an Arctic region of very high biogeochemical activity, Biogeosciences, 8, 1745–1754, doi:10.5194/bg-8-1745-2011.

Anderson, L.G., and Amon, R.M.W., (2015), DOC in the Arctic Ocean. In Biogeochemistry of Marine Dissolved Organic Matter, 2nd edition, edited by Dennis A. Hansell and Craig A. Carlson. pp. 609-633, Burlington, Academic Press, 2015

Anderson L.G., et al., (2009), Out-gassing of CO_2 from Siberian Shelf Seas by terrestrial organic matter decomposition. Geophys. Res. Lett., 36, L20601, doi:10.1029/2009GL040046.

Anderson, L. G. et al. (2016), Shelf-basin interaction along the Laptev - East Siberian Seas. Ocean Sci. Discuss. doi: 10.5194/os-2016-95.

Anderson, L.G., et al., (2017), Shelf –Basin interaction along the Laptev – East Siberian Seas. Ocean Science, 13, 349-363, doi:10.5194/os-13-349-2017.

Arrigo, K.R., van Dijken, G.L., (2011), Secular trends in Arctic Ocean net primary production. J. Geophys. Res., 116, C09011, doi:10.1029/2011JC007151.

Arrigo, K.R., et al., (2012), Massive phytoplankton blooms under Arctic sea ice. Science, 336 (6087), 1408-1408.

Ashjian, C.J., et al., (2003), Annual cycle in abundance, distribution, and size in relation to hydrography of important copepod species in the western Arctic Ocean. Deep-Sea Res., I, 50, 1235–1261, doi:10.1016/S0967-0637(03)00129-8.

AWI, (2013), Escaping the warmth: The Atlantic cod conquers the Arctic. Press Release. Alfred Wegener Institute, Bremerhaven, Germany.

Bates, N. R., Mathis, J. T., and Cooper, L. W. (2009), Ocean acidification and biologically induced seasonality of carbonate saturation states in the western Arctic Ocean. J. Geophys. Res., 114, C1007.

Bates, N. R., and Mathis, J. T., (2009), The Arctic Ocean marine carbon cycle: Evaluation of air-sea CO2 exchanges, ocean acidification impacts and potential feedbacks. Biogeosciences, 6, 2433–2459.

Barber, D.G., et al., (2015), Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone. Prog. Oceanogr., 139, 122-150

Bélanger, S., Babin, M., Tremblay, J.-É., (2013), Increasing cloudiness in Arctic damps the increase in phytoplankton primary production due to sea ice receding. Biogeosciences 10: 4087-4101. doi:10.5194/bg-10-4087-2013

Beszczynska-Möller, A., et al., (2011), A synthesis of exchanges through the main oceanic gateways to the Arctic Ocean. Oceanography, 24(3), 82-99, doi:10.5670/oceanog.2011.59.

Biastoch, A. et al., (2011), Rising Arctic Ocean temperatures can cause gas hydrate destabilization and ocean acidification. Geophys. Res. Lett., 38, L08602.

Björk, G., et al., (2007), Bathymetry and deep-water exchange across the central Lomonosov Ridge at 88–891N. Deep-Sea Res., I 54, 1197–1208.

Bluhm B.A., Carmack, E., and Kosobokova, K., (2015), A tale of two basins: An integrated physical and biological perspective of the deep Arctic Ocean. Prog. Oceanogr., 139:89-121.

Bluhm, B.A., and Grebmeier, J.M., (2011), Biodiversity – status and trends of benthic organisms. Arctic Report Card: Update for 2011.

Bluhm, B.A., and Gradinger, R., (2008), Regional variability in food availability for Arctic marine mammals. Ecological Applications, 18 (2) Supplement, S77–S96.

Bopp , L., et al., (2013), Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences., 10, 6225-6245.

Bowman, J. S., et al., (2012), Microbial community structure of Arctic multiyear sea ice and surface seawater by 454 sequencing of the 16S RNA gene. The ISME Journal 6, no. 1: 11-20.

Bowman, J. S., (2015), The relationship between sea ice bacterial community structure and biogeochemistry: A synthesis of current knowledge and known unknowns. Elementa: Science of the Anthropocene 3.1: 000072.

Campbell et al., (2009), Mesozooplankton prey preference and grazing impact in the western Arctic Ocean. Deep-Sea Res., II, 56, 1274–1289, doi:10.1016/j.dsr2.2008.10.027.

Carmack, E.C., et al., (1998), Thermohaline transitions. In Physical Processes in Lakes and Oceans, Coast. Estuar. Stud., 54 Vol. 54 Coast. Estuar. Stud. Editor J. Imberger, pp 179-186, AGU.

Carmack, E.C., and Chapman, D.C., (2003), Wind-driven shelf/basin exchange on an Arctic shelf: the joint roles of ice cover and shelf-break bathymetry. Geophys. Res. Lett., 30 (14), 1778. http://dx.doi.org/10.1029/2003GL017526.

Carmack, E. and Wassmann, P., (2006), Food webs and physical-biological coupling on pan-Arctic shelves: Unifying concepts and comphrehensive perspectives. Prog. Oceanogr., 71, 446-477.

Carothers, C., (2013), A survey of US halibut IFQ holders: Market participation, attitudes, and impacts. Marine Policy. 38:515-522.

Codispoti, L.A., et al., (2013), Synthesis of primary production in the Arctic Ocean: III. Nitrate and phosphate based estimates of net community production. Prog. Oceanogr., 110, 126-150.

Constable, et al., (2014), Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. Global Change Biology (2014), doi: 10.1111/gcb.12623

Dmitrenko, I.A., Kirillov, S.A., Tremblay, L.B., (2008), The long-term and interannual variability of summer freshwater storage over the eastern Siberian Shelf: implication for climatic change. J. Geophys. Res., 113, C03007.

Else, B.G.T., et al., (2012), Annual cycles of pCO2sw in the southeastern Beaufort Sea: new understandings of air-sea CO2 exchange in Arctic polynyas regions. J. Geophys. Res., 117, C00G13, doi: http://dx.doi.org/10.1029/2011JC007346

English, T.S., (1961), Some biological oceanographic observations in the central north Polar Sea, Drift Station Alpha, 1957-1958, Arctic Inst. of North America Scientific Report No.15. 1.

Ershova, E.A., et al., (2015), Long-term changes in summer zooplankton communities of the western Chukchi Sea, 1945–2012. Oceanography 28(3):100–115, http://dx.doi.org/10.5670/oceanog.2015.60.

Fahrbach, E., et al. (2001), Direct measurements of volume transports through Fram Strait. Polar Res., 20, 217-224.

Feng et al., (2016), Early ice retreat and ocean warming may induce copepod biogeographic boundary shifts in the Arctic Ocean. J.Geophys. Res., 121(8), 6137-6158.

Firth, E., et al., (2016), Bacterial use of choline to tolerate salinity shifts in sea-ice brines. Elementa: Science of the Anthropocene 4, no. 1.

Fossheim, M., et al., (2015), Recent warming leads to a rapid borealization of fish communities in the Arctic. Nature Climate Change, 5, 673-677, doi:10.1038/nclimate2647

Francis, J. A. and Vavrus, S. J., (2015), Evidence for a wavier jet stream in response to rapid Arctic warming. Environ. Res. Lett. 10, 014005.

Friedlingstein, P., et al., (2006), Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison, J. Clim., 19, 3337-3353.

Fripiat F, et al., (2014), New insights into sea ice nitrogen biogeochemical dynamics from the nitrogen isotopes. Global Biogeochem. Cycl., 28(2), 115–130. doi: 10.1002/2013GB004729.

Gammelsrød et al., (2009), Mass and heat transports in the NE Barents Sea: Observations and models. J. Mar. Sys., 75, 56-69, doi:10.1016/j.jmarsys.2008.07.010.

Gosselin et al., (1997), New measurements of phytoplankton and ice algal production in the Arctic Ocean. Deep-Sea Res., II, 44(8), 1623-1644.

Grebmeier, J.M., et al., (2015). Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. Prog. Oceanogr., 136:92–114, http://dx.doi.org/10.1016/j.pocean.2015.05.006.

Grotenfendt, K., et al., (1998), Is the Arctic Ocean warming? J. Geophys. Res., 103(C12), 27,679– 27,687.

Gu, H., et al., (2013), Morphology, phylogeny, and toxicity of Atama complex (Dinophyceae) from the Chukchi Sea. Polar Biol 36, 427–436

Hansen, B., et al., (2015), Transport of volume, heat, and salt towards the Arctic in the Faroe Current 1993–2013. Ocean Sci. 11, 743–757.

Hill, V.J., et al., (2013), Synthesis of integrated primary production in the Arctic Ocean: II. In situ and remotely sensed estimates. Prog. Oceanogr., 110, 107-125.

Hirche, H.-J., and Kosobokova, K., (2007), Distribution of Calanus finmarchicus in the northern North Atlantic and Arctic Ocean - Expatriation and potential colonization. Deep-Sea Res. Pt II, 54, 2729–2747.

Ingvaldsen, R.B., Asplin, L. and Loeng, H., (2004), The seasonal cycle in the Atlantic transport to the Barents Sea during the years 1997–2001. Cont. Shelf Res., 24 1015–1032, doi:10.1016/j.csr.2004.02.011.

Jackson L.C., et al., (2015), Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. Clim. Dyn. 45, 3299–3316.

Jakobsson, M., et al., (2012), The international bathymetric chart of the Arctic Ocean (IBCAO) Version 3.0. Geophys. Res. Lett., 39, L12609, doi: 10.1029/2012GL052219.

Ji, R., et al., (2012), Life history and biogeography of Calanus copepods in the Arctic Ocean: an individual-based modeling study. Prog. Oceanogr., 96, 40-56.

Ji, R., Jin, M., and Varpe, O., (2013), Sea ice phenology and timing of primary production pulses in the Arctic Ocean. Global Change Biology 19, 734-741.

Kahru, M., et al., (2016), Effects of sea ice cover on satellite-detected primary production in the Arctic Ocean. Biol. Lett. 12: 20160223.

Kedra, M., et al., (2015), Status and trends in the structure of Arctic benthic food webs. Polar Research, 34, 23775, doi.org/10.3402/polar.v34.23775

Khatiwala, S. et al., (2013), Global ocean storage of anthropogenic carbon. Biogeosciences, 10, 2169-2191-

Kinnard, C., et al., (2011), Reconstructed change in Arctic sea ice over the past 1,450 years. Nature, 279, 509-512.

Kosobokova, K.N., Hirche, H.J., (2009), Biomass of zooplankton in the eastern Arctic Ocean—a baseline study. Prog. Oceanogr., 82, 265–280, doi: 10.1016/j.pocean.2009.07.006.

Kosobokova KN, Hopcroft RR (2010) Diversity and vertical distribution of mesozooplankton in the Arctic's Canada Basin. Deep Sea Res II 57:96–110, doi: 10.1016/j.dsr2.2009.08.009.

Kwok, R., and Rothrock, D.A., (2009), Decline in Arctic sea ice thickness from submarine and ICESat records: 1958-2008. Geophys. Res. Lett., 36, L15501, doi:10.1029/2009GL039035.

Kwok, R, Cunningham, G.F., (2015), Variability of Arctic sea ice thickness and volume from CryoSat-2. Phil. Trans. R. Soc. A 373, doi:10.1098/rsta.2014.0157.

Lammers, R.B., et al., (2001), Assessment of contemporary Arctic river runoff based on observational discharge records. J. Geophys. Res., 10, 63321–3334.

Lefebvre, K.A., et al., (2016), Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. Harmful Algae 55, 13-24.

Le Quéré, C. et al., (2016), Global carbon budget 2016, Earth Syst. Sci. Data, 8, 605-649.

Leu, E., et al., (2011), Consequences of changing sea-ice cover for primary and secondary producers in the European Arctic shelf seas: Timing quantity, and quality. Prog. Oceanogr., 90, 18–32.

Leu, E., et al., (2015), Arctic spring awakening – Steering principles behind the phenology of vernal ice algal blooms. Prog. Oceanogr., 139, 151-170.

Li, W.K.W., et al., (2009). Smallest algae thrive as the Arctic Ocean freshens. Science, 326, 539-539.

Li, W.K.W., et al., (2013), Space-for-time substitution in predicting the state of picoplankton and nanoplankton in a changing Arctic Ocean. J Geophys. Res., 118(10), 5750-5759.

Liljedahl, A.K. et al., (2016), Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. Nat. Geosci., 9, 312-318.

Lovejoy, C., Massana, R., and Pedrós-Alió, C., (2006), Diversity and distribution of marine microbial eukaryotes in the Arctic Ocean and adjacent seas. Appl. Environ. Microbiol., 72(5), 3085-3095.

Lovejoy, C., and Potvin, M., (2011), Microbial eukaryotic distribution in a dynamic Beaufort Sea and the Arctic Ocean. J. Plankton Res., 33(3), 431-444, doi:10.1093/plankt/fbq124.

Lozier, M.S., (2010), Deconstructing the Conveyor Belt. Science, 328, 1507-1511, doi:10.1126/science.1189250.

Macdonald, R.W., et al., (1999), Connections among ice, runoff and atmospheric forcing in the Beaufort Gyre. Geophys. Res. Lett., 26, 2223–2226.

Macdonald, R.W., Sakshaug, E., and Stein, R., (2004), The Arctic Ocean: modern status and recent climate change. In: The Organic Carbon Cycle in the Arctic Ocean. Ed. by R. Stein and R.W. Macdonald, pp. 297–322, Springer, Berlin.

MacGilchrist, G.A., et al., (2014), The Arctic Ocean carbon sink. Deep-Sea Res. Part I, 86, 39-55.

Makshtas A.P., et al.,(2011), Climate of the Hydrometeorological Observatory Tiksi region. In Meteorological and Geophysical Investigations, Paulsen, 49-74.

Matrai, P.A., et al., (2013), Synthesis of primary production in the Arctic Ocean: I. Surface waters, 1954-2007. Prog. Oceanogr. 110: 93-106.

McClelland J.W., et al., (2006), A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century. Geophys. Res. Lett., 33, doi:10.1029/2006GL025753.

McLaughlin, F.A., et al., (1996), Physical and geochemical properties across the Atlantic/Pacific water mass front in the southern Canadian basin. J. Geophys. Res., 101, 1183-1197.

McLaughlin, F.A., et al., (2009), Joint effects of boundary currents and thermohaline intrusions on the warming of Atlantic water in the Canada Basin, 1993-2007. J. Geophys. Res., 114, C00A12, doi:10.1029/2008JC005001.

Meltofte, H. (ed), 2013, Arctic Biodiversity Assessment. Status and trends in Arctic biodiversity. Conservation of Arctic Flora and Fauna, Akureyri, Iceland.

Miller, L.A., et al., (2011), Carbon dynamics in sea ice: a winter flux time series. J. Geophys. Res. 116, C02028, doi: http://dx.doi.org/10.1029/2009JC006058

Moore S.E., et al., (2014), Marine fishes, birds and mammals as sentinels of ecosystem variability and reorganization in the Pacific Arctic region. In J.M. Grebmeier & W. Maslowski (eds.): Ecosystem status and trends in a rapidly changing environment. Pp. 337–392. Dordrecht, Netherlands: Springer.

Natsuike, M., et al., (2013), Abundance and distribution of toxic Alexandrium tamarense resting cysts in the sediments of the Chukchi Sea and the eastern Bering Sea. Harmful Algae 27, 52−59

Nelson, R.J., et al., (2009), Penetration of Pacific zooplankton into the western Arctic Ocean tracked with molecular population genetics. Mar. Ecol. Prog. Ser., 381, 129–138.

Nelson, R.J., et al., (2014), Biodiversity and Biogeography of the Lower Trophic Taxa of the Pacific Arctic Region: Sensitivities to Climate Change. In: The Pacific Arctic Region: Ecosystem Status and Trends in a Rapidly Changing Environment, Ed: J.M. Grebmeier, W. Maslowski, pp.269-336, Springer Netherlands, DOI: 10.1007/978-94-017-8863-2_10.

NPFMC, (2009), Fishery Management Plan for Fish Resources of the Arctic Management Area, North Pacific Fishery Management Council, Anchorage, Alaska, 158 pp.

Olsen, A., Anderson, L.G., and Heinze, C., (2015), Arctic Carbon Cycle: Patterns, Impacts and Possible Changes. Ed B. Evengård et al., The New Arctic, DOI 10.1007/978-3-319-17602-4_8

Omar, A. M., et al., (2005), Sea ice and brine formation in Storfjorden: implications for the Arctic wintertime air-sea CO_2 flux., in The Nordic Seas: an integrated perspective, eds. H. Drange, et a., pp. 177-188, AGU Geophysical Monograph.

Overland, J.E., et al., (2015), The melting Arctic and mid-latitude weather patterns: Are they connected? J. Climate, doi: 10.1175/JCLI-D-14-00822.1

Overland, J.E., et al., (2016), Nonlinear response of mid-latitude weather to the changing Arctic. *Nature Clim. Change*, *6*, 992–999, doi: 10.1038/nclimate3121.

Paulsen, M.L., et al., (2016), Sunechococcus in the Atlantic Gateway to the Arctic Ocean. Front. Mar. Sci., 05 October 2016

Pithan, F., and Mauritsen, T., (2014), Arctic amplification dominated by temperature feedbacks in contemporary climate models. Nature Geoscience, doi: 10.1038/ngeo2071.

Pnyushkov, A., et al., (2015), Structure and variability of the boundary current in the Eurasian Basin of the Arctic Ocean, Deep Sea Res., 101, 80–97, doi:10.1016/j.dsr.2015.03.001.

Polyakov, I.V., et al. (2005), One more step toward a warmer Arctic. Geophys. Res. Lett., 32, doi:10.1029/2005GL023740.

Polyakov, I.V., et al., (2017), Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean Science 356, 285–291.

Pomeroy, L.R., 1997. Primary production in the Arctic Ocean estimated from dissolved oxygen. J Mar. Syst., 10(1), 1-8.

Popova, E.E., et al., (2012), What controls primary production in the Arctic Ocean? Results from an intercomparison of five general circulation models with biogeochemistry, J. Geophys. Res., 117, C00D12, doi:10.1029/2011JC007112.

Rainville, L. Lee, C.M., and Woodgate, R.A., (2011), Impact of wind-driven mixing in the Arctic Ocean. Oceanography 24(3), 136-145, doi:10.5670/oceanog.2011.65.

Renaud, P.E., et al., (2012), Is the poleward expansion by Atlantic cod and haddock threatening native polar cod, Boreogadus saida? Polar Biol (2012) 35:401–412DOI 10.1007/s00300-011-1085-z

Riebesell, U., and Gattuso, J.-P., (2014), Lessons learned from ocean acidification research.Nature Climate Change, 5, 12–14, doi: 10.1038/nclimate2456

Richlen, M.L., et al., (2016), Distribution of Alexandrium fundyense (Dinophyceae) cysts in Greenland and Iceland, with an emphasis on viability and growth in the Arctic. Mar. Ecol. Prog. Ser. 546: 33-46. doi: 10.3354/meps11660

Roach et al., (1995), Direct measurements of transport and water properties through the Bering Strait. J. Geophys. Res., 100(C9) 18443-18457.

Rigor, I.G., Wallace, J.M., and Colony, R.L., (2002), Response of sea ice to the Arctic Oscillation. J. Climate, 15, 2648-2663.

Rudels, B., Anderson, L.G., and Jones, E.P., (1996), Formation and evolution of the surface mixed layer and halocline of the Arctic Ocean. J. Geophys. Res., 101, 8807-8821.

Rudels, B, Friedrich, H.J., and Quadfasel, D., (1999), The Arctic circumpolar boundary current. Deep-Sea Res., Part II, 46, 1023-1062.

Rudels, B., and Friedrich, H., (2000), The transformation of Atlantic Water in the Arctic Ocean and their significance for the freshwater budget. In The Freshwater Budget of the Arctic Ocean Vol. 70 edited by L.L. Lewis et al., pp. 503-532, Kluwer Academic Publishers.

Rudels, B. et al., (2000), Water mass distribution in Fram Strait and over the Yermak Plateau in summer 1997. Ann. Geophys.-Atmos. Hydrospheres Space Sci. 18, 687-705.

Rudels, B., et al., (2012), Observations in the ocean, in Arctic Climate Change: The ACSYS Decade and Beyond, Atmos. Oceanogr. Sci. Libr., vol. 43, edited by P. Lemke and H.-W. Jacobi, doi:10.1007/978-94-007–2027-5_4. pp. 117–198, VC Springer Science1Business Media B.V.

Rudels, B. et al., (2013), Observations of water masses and circulation with focus on the Eurasian Basin of the Arctic Ocean from the 1990s to the late 2000s. Ocean Sci., 9, 147–169, doi:10.5194/os-9–147-2013.

Serreze, M.C. et al., (2006), The large-scale freshwater cycle of the Arctic. J. Geophys. Res., 111: C11010.

Serreze, M., and Barry, R., (2011), Processes and impacts of Arctic amplification: A research synthesis. Global and Planetary Change, 77, 85-96.

Serreze, MC,, and Stroeve, J., (2015), Arctic sea ice trends, variability and implications for seasonal ice forecasting. Phil. Trans. R. Soc. A 373, doi:10.1098/rsta.2014.0159.

Shakova, N., et al., (2010a), Geochemical and geophysical evidence of methane release over the East Siberian Arctic Shelf. J. Geophys. Res., 115, C08007.

Shakhova, N. et al., (2010b), Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf. Science, 327, 1246–1250. doi:10.1126/science.1182221.

Shakova, N., et al., (2014), Ebullition and storm-induced methane release from the East Siberian Arctic Shelf. Nat. Geosci., 7, 64-70. doi: 10.1038/ngeo2007.

Sherr, E.B., Sherr, B.F., and Fessenden, L., (1997), Heterotrophic protists in the central Arctic Ocean. Deep-Sea Research II 44, 1665–1682.

Sherr, E.B., et al., (2003), Temporal and spatial variation in stocks of autotrophic and heterotrophic microbes in the upper water column of the central Arctic Ocean. Deep-Sea Res. I 50, 557-571

Sherr, E.B., Sherr, B.F., and Hartz, A.J., (2009), Microzooplankton grazing impact in the western Arctic Ocean. Deep-Sea Res., II, 56, 1264–1273.

Sigman, D.M., and *Boyle*, E.A., (2000), Glacial/interglacial variations in atmospheric carbon dioxide. *Nature* 407, 859–869.

Slagstad, D., Ellingsen, I.H., Wassmann, P., (2011), Evaluating primary and secondary production in an Arctic Ocean void of summer sea ice: an experimental simulation approach. Prog. Ocean., 90 (1–4), 117–131.

Smedsrud, L.H., et al., (2013), The role of the Barents Sea in the Arctic climate system. Rev. Geophys. 51, doi: 8755-1209/13/10.1002/rog.20017

Smith, L. C., et al., (2005), Disappearing Arctic lakes. Science, 308, 1429.

Smith Jr., W.O., and Sakshaug, E., (1990), Polar phytoplankton. In: Smith, W.O., Jr. (Ed.), Polar Oceanography, Part B Chemistry, Biology and Geology. pp. 477–525, Academic Press, San Diego,.

Søreide, J.E., et al., (2010), Timing of blooms, algal food quality and Calanus glacialis reproduction and growth in a changing Arctic. Global Change Biology, doi: 10.1111/j.1365-2486.2010.02175.x

Steele, M., and Boyd, T., (1998), Retreat of the cold halocline layer in the Arctic Ocean. J. Geophys. Res., 103, 10419-10435, doi:10.1029/98JC00580.

Stein, R., and Macdonald, R.W., (2004), Preface, In: The organic carbon cycle in the Arctic Ocean. Heidelberg: Springer.

Steinacher, M., et al., (2009), Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. Biogeosciences, 6, 515–533.

Stiasny, M.H., et al., (2016), Ocean Acidification Effects on Atlantic Cod Larval Survival and Recruitment to the Fished Population. PLoS ONE 11(8), e0155448. doi:10.1371/journal.pone.0155448.

Stroeve, J.C., et al., (2012), The Arctic's rapidly shrinking sea ice cover: A research synthesis. Clim. Change, 110, 1005–1027, doi:10.1007/s10584-011-0101-1.

Swift, J.H., et al., (2005), Long-term variability of Arctic Ocean waters: evidence from a reanalysis of the EWG data set. J. Geophys. Res., 110, doi:10.1029/2004JC002312.

Thompson, D.W.J., and Wallace, J.M., (1998), Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys. Res. Lett., 25, 1297-1300, doi:10.1029/98GL00950.

Thornton, B. F., et al., (2016), Methane fluxes from the sea to the atmosphere across the Siberian shelf seas. Geophys. Res. Lett., 43, 5869-

Timmermans, M.-L., Garrett, C., and Carmack, E., (2003), The thermohaline structure and evolution of the deep waters in the Canada Basin, Arctic Ocean. Deep-Sea Res., Part I, 50, 1305-1321.

Tremblay, J.E., et al., (2002), Impact of the large-scale Arctic circulation and the North Water Polynya on nutrient inventories in Baffin Bay. J. Geophys. Res., 107, doi:10.1029/2000JC00,595.

Tremblay, J.-É., et al., (2015), Global and regional drivers of nutrient supply, primary production, and CO2 drawdown in the changing Arctic Ocean. Prog. Ocean., 139, 171–196, http://dx.doi.org/10.1016/j.pocean.2015.08.009.

Walczowski, W., (2014), Atlantic Water in the Nordic Seas, Properties, Variability, Climate Importance. 188 pp, Springer International Publishing Switzerland.

Ware, C., et al., (2016), Biological introduction risks from shipping in a warming Arctic. J. App. Ecol. 52, 340-349. doi: 10.1111/1365-2664.12566

Wassmann, P., and Reigstad, M., (2011), Future Arctic Ocean seasonal ice zones and implications for pelagic–benthic coupling. Oceanography, 24, 220–231.

Wassmann, P.F., **Slagstad, D., and Ellingsen, I.H.,** (2010), Primary production and climatic variability in the European sector of the Arctic Ocean prior to 2007: preliminary results. Polar Biology, 33(12), 1641 – 1650, doi: 10.1007/s00300-010-0839-3.

Wassmann, P. et al., (2015), The contiguous domains of Arctic Ocean advection: Trails of life and death. Prog. Ocean., 139, 42-65.

Wheeler, P. J., et al., (1996), Active cycling of organic carbon in the central Arctic ocean. Nature, 380, 697–699.

Woodgate, R.A., et al. (2001), The Arctic Ocean boundary current along the Eurasian slope and the adjacent Lomonosov Ridge: Water mass properties, transports and transformations from moored instruments. Deep-Sea Res., Part I, 48, 1757-1792.

Woodgate, R.A., Aagaard, K., and Weingartner, T.J., (2005a), Monthly temperature, salinity, and transport variability of the Bering Strait throughflow. Geophys. Res. Lett., 32, L04601, doi:10.1029/2004GL021880.

Woodgate, R.A. et al., (2007), Atlantic Water Circulation over the Mendeleev Ridge and Chukchi Borderland from Thermohaline Intrusions and Water Mass Properties. J. Geophys. Res., 112, C02005, doi:10.1029/2005JC003416.

Yamamoto-Kawai, M. et al., (2009), Aragonite undersaturation in the Arctic Ocean; effects of ocean acidification and sea ice melt. Science, 326, 1098, doi:10.1126/science.1174190

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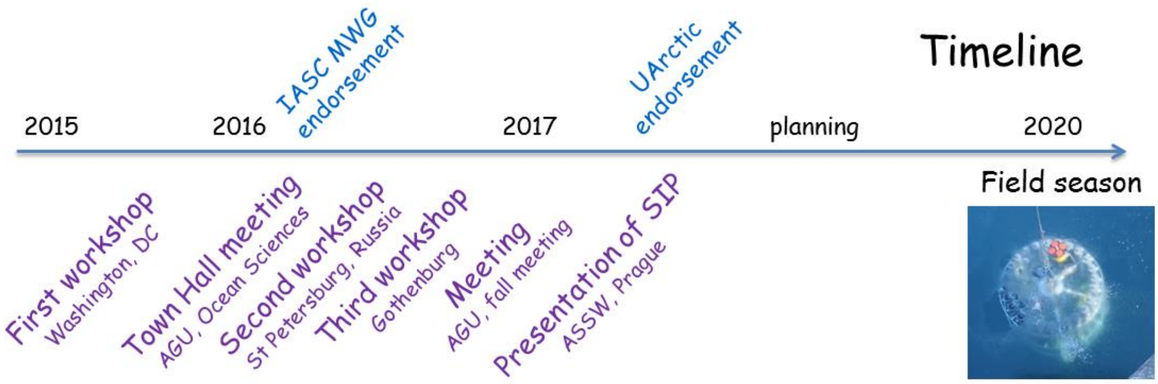
Synoptic Arctic *Survey*

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.

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


German consulate, St Petersburg, 1 June, 2016


Univ. Gothenburg, 28-28 September, 2016