ART

The Arctic in Rapid Transition (ART) is a proposed integrative, multi-disciplinary, long-term pan-Arctic program to study changes and feedbacks with respect to physical characteristics and biogeochemical cycles of the Arctic Ocean and its biological productive capacity.

Arctic in Rapid Transition

Science Plan

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EXECUTIVE SUMMARY

The Arctic is undergoing rapid transformations that have brought the Arctic Ocean to the top of international political agendas. Predicting future conditions of the Arctic Ocean system requires scientific knowledge of its present status as well as a process-based understanding of the mechanisms of change. The Arctic in Rapid Transition (ART) initiative is an integrative, international, interdisciplinary pan-Arctic program to study changes and feedbacks among the physical and biogeochemical components of the Arctic Ocean and their ultimate impacts on biological productivity. The goal of ART is to develop priorities for Arctic marine science over the next decade. Three overarching questions form the basis of the ART science plan:

(1) How were past transitions in sea ice connected to energy flows, elemental cycling, biological diversity and productivity, and how do these compare to present and projected shifts?
(2) How will biogeochemical cycling respond to transitions in terrestrial, gateway and shelf-to-basin fluxes?
(3) How do Arctic Ocean organisms and ecosystems respond to environmental transitions including temperature, stratification, ice conditions, and pH?

The integrated approach developed to answer the ART key scientific questions comprises: (a) process studies and observations to reveal mechanisms, (b) the establishment of links to existing monitoring programs, (c) the evaluation of geological records to extend time-series, and (d) the improvement of our modeling capabilities of climate-induced transitions. In order to develop an implementation plan for the ART initiative, an international and interdisciplinary workshop is currently planned to take place in Winnipeg, Canada in October 2010.

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1.0 RATIONALE AND BACKGROUND

The Arctic is a unique and important part of the Earth system: environmentally, socially, economically, and politically. It is now experiencing some of the most rapid transformations on the planet, from severe changes in its climate to impacts from globalization and other socioeconomic issues. How the Arctic system works, how it is changing, and what it will be like in the future are important questions being asked by policy makers, land-use managers, and people who reside in the Arctic. It is thus essential that decision makers and stakeholders draw on the latest and best data and information available regarding ongoing and projected Arctic changes to effectively plan for, mitigate, and adapt to the emerging impacts. Providing this information is clearly the responsibility and goal of the scientific community, and requires a truly integrated effort.

A step toward improving our capacity to predict future Arctic change was undertaken with the Second International Conference on Arctic Research Planning (ICARP II) meetings in 2005 and 2006, which brought together scientists, policy-makers, research managers, Arctic residents, and other stakeholders interested in the future of the Arctic region. As the ICARP II process came to a close, the Arctic in Rapid Transition (ART) Initiative was developed in an effort to synthesize the several resulting ICARP II science plans specific to the Arctic marine environment (WG 3: Arctic coastal processes, WG 4: Deep central basin of the Arctic Ocean, WG 5: Arctic margins and gateways, and WG 6: Arctic shelf seas). As a first step the ART White Paper was presented to, and accepted by, the Arctic Ocean Science Board during the Arctic Science Summit Week in Bergen in March 2009. In order to initiate the development of the actual science plan, the ART Initiation Workshop was subsequently organized in November 2009, hosted by the International Arctic Research Center at the University of Fairbanks, Alaska (see Appendix I). The meeting was organized around discussions and reviews of the seven key questions posed in the ART White Paper by multidisciplinary working groups. This resulted in a further narrowing of the critical topics into three main questions focusing on sea ice, land-ocean interactions, and ecosystem responses.

To this end, **the ART Initiative is an integrative, international, multidisciplinary, long-term pan-Arctic program to study changes and feedbacks among the physical and biogeochemical components of the Arctic Ocean and their ultimate impacts on biological productivity.**

The priorities are inspired by the dramatic changes and transitions that have occurred in the Arctic since the ICARP reports were concluded in 2005, the need to build on new initiatives and knowledge resulting from the International Polar Year (IPY) effort of 2007-2008, and the immediate and pressing need for synthesized knowledge required by policy-makers, land-use managers, and people who reside in the Arctic. ART also emphasizes the involvement of early-career scientists, who comprise the majority of the Steering Group, to create a new synergy between scientific generations and to incorporate innovative ideas.

This document defines a science plan that presents the overarching questions and the scientific infrastructure that will be used to address the changing environment in the Arctic and the issues mentioned above. To improve our ability to plan for changing environmental conditions in the Arctic, we need to improve our understanding of (i) the spatial and temporal variability of ice-cover and its relationship to atmospheric and ocean circulation on seasonal, decadal and millennial/orbital timescales, and (ii) how these changes impact patterns of productivity and resource use. Developing links between sea ice and the physical, biological, and geochemical feedback processes and forcing mechanisms, provides a way to improve forecasts of future ice conditions and plausible consequences for those who rely on Arctic resources for cultural and socio-economic well-being.

2.0 THE ARCTIC IN RAPID TRANSITION (ART)

The Arctic Ocean is now in a state of rapid transition with tremendous economic, social and environmental consequences. This is best exemplified by the marked reduction in the age, thickness and extent of the Arctic sea ice cover witnessed in instrumental records over the last 30 years (Serreze et al., 2007; Maslanik et al. 2007; Figure 1).

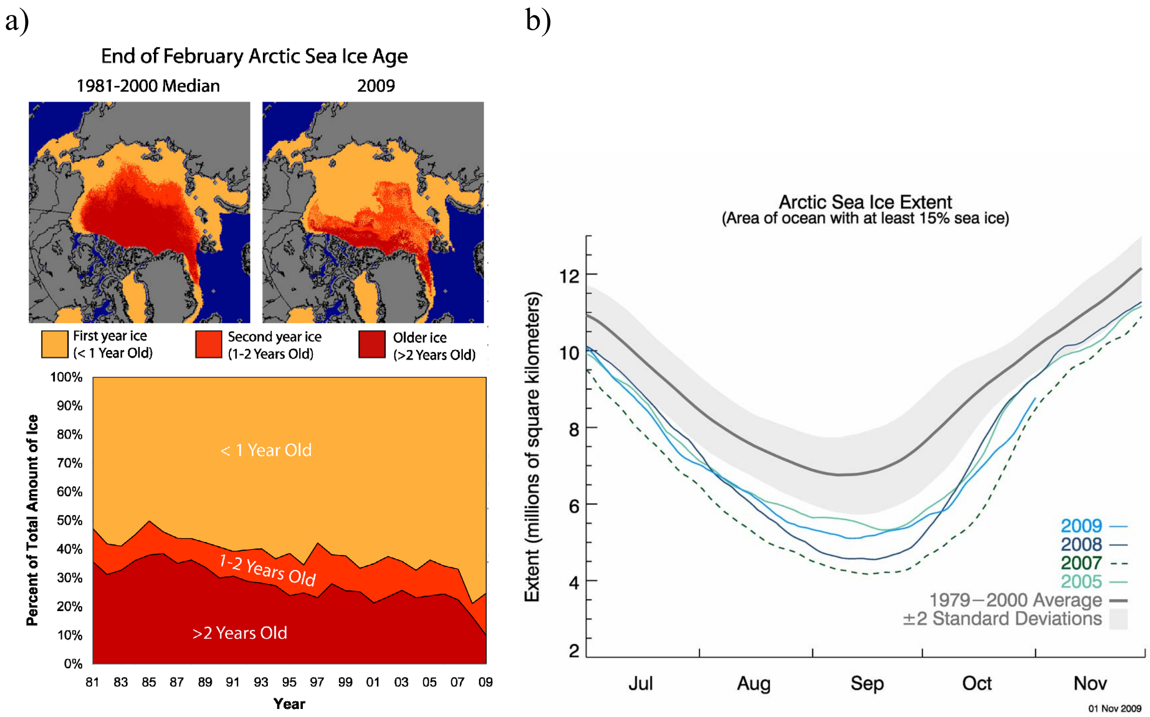

Figure 1: (a) Age of the Arctic sea ice at the end of February in 2009 compared to the 1981-2000 median and from 1981 to 2009. Ice older than two years was <10% total extent in 2009; (b) Extent of the Arctic summer sea ice in 2009, 2008, 2007, 2005, and average summer extent from 1979 to 2000. (Source: National Snow and Ice Data Center, http://nsidc.org/arcticseaicenews).

Alarmingly, this reduction is occurring more rapidly than predicted by global climate models (Stroeve et al., 2007; IPCC, 2007). Inabilities to predict the response of the Arctic ice cover in the Arctic arise from uncertainties in complex feedback processes, forcing mechanisms and initial boundary conditions of the ice-ocean-atmosphere system. Within a planning and mitigation framework, the overall mismatch between observed and predicted patterns exasperates the conceptual gap between the forecasted reduction in sea ice cover under future CO_2 projections, and how this translates into regional socio-economic impacts.

The goal of this proposal is to develop a research program capable of uniting the multidisciplinary and multinational group of scientists needed to address the particular challenges that environmental change presents in the Arctic Ocean. For example, observed changes in ice cover impact the physical, chemical, and biological environments that form the basis for established ecosystems as well as the terrestrial and atmospheric boundary conditions (e.g. *via* coastal erosion and *via* ocean-atmosphere heat flux). Many of these changes cannot be predicted based on current knowledge. There is a growing consensus that we are passing 'tipping' points and exceeding ecological thresholds (Grebmeier et al., 2006; Wassmann et al., 2008; Andersen et al 2009). In this new state, physical, chemical, and biological linkages and feedbacks within the ocean-ice-atmosphere system are to a large extent unknown.

To answer questions of policy-makers, stakeholders, and communities we need to know how the future Arctic will look, and we need to develop a scientific infrastructure and coherent strategy to be applied across funding agencies. ART will focus on integrating data on past and present transitional states of the Arctic that can be used synergistically with ongoing monitoring, observing and modeling efforts, to better assess future changes. Specific aims are to develop process-oriented perspectives on the variability of sea ice-related processes and relationships to biological productivity that merge knowledge on centennial through millennial/orbital timescales (acquired from geologic records) with decadal through seasonal variations (recorded in instrumental and observational records).

The overarching objective of ART is to help bridge processes and ecosystem responses on shelves, margins and the central Arctic Ocean; all of which are facing rapid transitions. Such knowledge is necessary to improve our ability to understand, predict and adapt to current and future Arctic transitions.

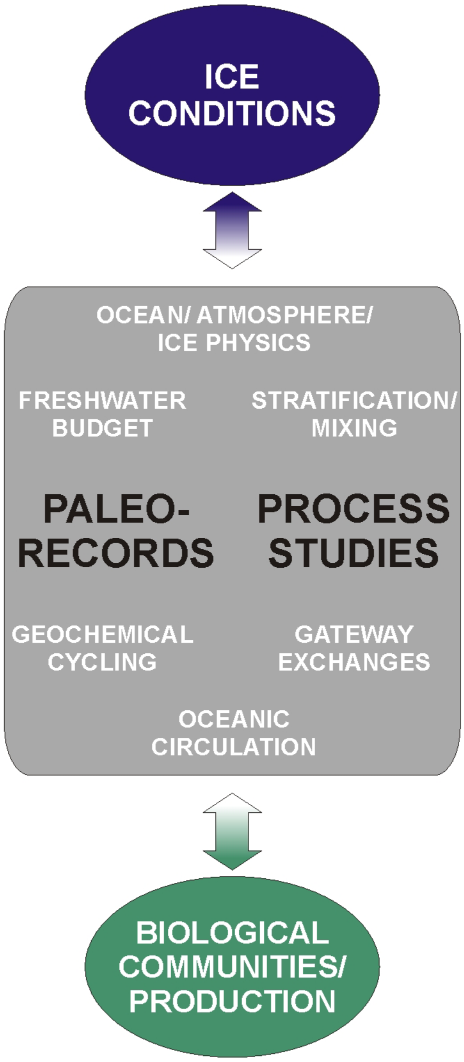

Figure 2: Conceptual schematics showing various processes involved in linkages between sea ice and biological communities and productivity, emphasizing the need for a multi-disciplinary approach in ART.

2.1 Definition of terms

The ART Program is framed by an appropriate terminology that is important to define. The key term *Transition* has been adopted because we argue that the Arctic Ocean is currently experiencing a phase of disequilibrium between two states of relative stability. In ecosystems, as in societal systems, two alternative stable states are separated by a critical threshold that can be induced by various anthropogenic, climatic or geological forcings (Scheffer et al., 2009). In the case of the Arctic Ocean system, we do not know if the critical thresholds have already been passed or are now being approached. Moreover, region-specific effects (e.g. overfishing) are able to produce a local shift towards a new steady state, while other areas of the Arctic Ocean can remain unaffected or be resilient to this shift. In a system in transition, abrupt change can also occur when the system is forced to a new state at a rate that is more rapid than the rate of change of the external forcing (Alley et al., 2003). Hence, the amplification of climate warming in high-northern latitudes (IPCC, 2007) provides a compelling illustration that the Arctic Ocean system is likely in a phase of rapid transition with respect to the global rate of warming.

One of the main originalities of the ART Program is the inclusion of both paleo-records and process-oriented studies in order to understand the current transition and forecast its future state. The temporal scope of ART is diverse and focuses on *short*- and *long-term* events. We propose that *short-term* describes processes that range from less than daily up to yearly timescales, while *long-term* defines time intervals of decadal- to millennial/orbital-scale variability.

ART has also adopted the Arctic Ocean typology of Carmack et al. (2006) that distinguishes the pan-Arctic shelves among *inflow*, *interior* and *outflow shelves* (Figure 3). In brief, *inflow shelves* receive waters from the Atlantic and Pacific oceans that are modified by physical and biogeochemical processes during their transit. Waters exiting these shelves subduct at the shelfbreak and influence property distribution patterns within the Arctic basins. The *interior shelves* are influenced by the major Arctic rivers and possess generally a positive estuarine circulation in summer (i.e. plume spreading) and a negative one (i.e. brine release) in winter. The *outflow shelves* allow the passage of Arctic waters (e.g. through buoyancy-boundary or shelfbreak currents) back into the North Atlantic via the Canadian Archipelago, Baffin Bay and eastern Greenland Sea. The connections between the Arctic and sub-Arctic oceans, in particular the Fram Strait and Bering Strait, are regarded as *gateways*.

a) b)

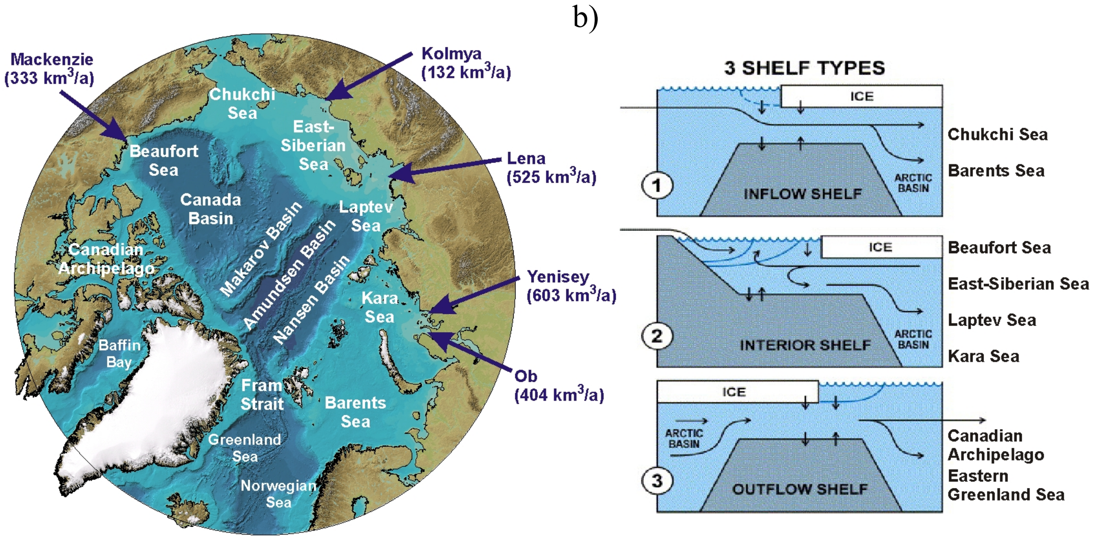

Figure 3: (a) International Chart of the Arctic Ocean with the central basins, continental shelves, major rivers and associated freshwater discharge; (b) The three different Arctic Ocean shelf types: inflow, interior and outflow shelves, according to Carmack and Wassmann (2006).

2.2 Overarching scientific questions

ART is about linkages and forcing factors in the Arctic Ocean and proposes scientific questions that serve to unify various disciplines rather than questions along traditional disciplinary partitions. In order to study changes and feedbacks among the physical characteristics and biogeochemical cycles of the Arctic Ocean and to predict the future Arctic Ocean, the ART Initiative will focus on three key questions that are divided into more detailed sub-questions (see section 4.0).

Sea Ice and Past Transitions

- How were past transitions in sea ice connected to energy flows, elemental cycling, biological diversity and productivity, and how do these compare to present and projected shifts?

Land-Ocean-Gateway Interactions

- How will biogeochemical cycling respond to transitions in terrestrial, gateway and shelf-to-basin fluxes?

Ecosystems and Organisms

- How do Arctic Ocean organisms and ecosystems respond to environmental transitions including temperature, stratification, ice conditions, and pH?

3.0 SCIENTIFIC FRAMEWORK

The goal of the ART Initiative is to integrate, update and develop priorities for Arctic marine science over the next decade. More specifically, the ART Initiative will focus on bridging gaps in knowledge not only across disciplinary boundaries (e.g., biology, geochemistry, geology, meteorology, physical oceanography), but also across geographic (e.g., international boundaries, shelves, margins, and the central Arctic Ocean) and temporal boundaries (e.g., paleo/geological records, current observations, and future modeling studies). The approach of the ART Initiative will provide a means to better understand and predict future change in the Arctic Ocean system, with a particular focus on the ultimate consequences for biological productivity.

The ART Initiative will leverage knowledge and resources from additional ongoing science programs, while addressing the need for an integrated approach for understanding the Arctic Ocean system including the biological ramifications. To this end, ART aims to harness the momentum from existing and past international initiatives by nurturing connections between ongoing programs, fostering the synthesis and integration of existing knowledge and proposing specific tasks to fill knowledge gaps. In particular, ART will address the linkages and feedbacks between physical drivers, biological communities, and biogeochemical cycles in the Arctic Ocean, and how these impact regional productive capacities and interact with global climate dynamics.

In addition to the plethora of programs undertaken during the International Polar Year 2007–2008, there are numerous large international initiatives devoted to understanding climate change in the Arctic Ocean and broader pan-Arctic region. These include iAOOS (integrated Arctic Ocean Observing System), DAMOCLES (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies), ISAC (International Study on Arctic Change), SEARCH (Study of Environmental Arctic Change), and SAON (Sustaining Arctic Observing Networks). Together, these activities form a basis for a continuing international effort for the collection and analysis of a broad knowledge base of the Arctic Ocean and the Arctic system as a whole.

Many supplementary science programs are smaller in scope, focusing on regionally-specific studies. For example, ART will help to bridge gaps between science programs that study coastal regions, e.g., ACD (Arctic Coastal Dynamics) and LOICZ (Land Ocean Interactions in the Coastal Zone) and NACP (North American Carbon Program) as well as shelf regions, e.g., SBI (Arctic Shelf Basin Interaction, Phase III) and ICE-ECO (Comparative Studies of Ice-Associated Ecosystems in Changing Arctic Shelf Seas). There are also observational programs centered on geographically-specific studies that include C3O (Canada 3 Oceans), CFL (Circumpolar Flaw Lead System Study), ESSAS (Ecosystem Studies of Sub-Arctic Seas), ArcticNet, NABOS (Nansen and Amundsen Basins Observational System), and BEST (Bering Ecosystem STudy), or ecosystem responses to changing climate like ATP (Arctic Tipping Points). Moreover, there are ongoing programs specifically dedicated to paleo-environmental reconstructions, e.g., APEX (Arctic Paleoclimate and its Extremes); WARMPAST (Arctic Ocean Warming in the Past); and Past4Future. More information about these and other related programs can be found in Appendix I.

Not all of the aforementioned science programs are specifically focused on the Arctic Ocean system. Those that are may be relatively specific in scope in terms of geographic regions or paleo vs. observational studies. ART will help to bridge these gaps and allow for an international, interdisciplinary science program for the Arctic Ocean that integrates past, present, and future. Furthermore, biological observations are severely under-represented in most of the current observing and science programs for the Arctic Ocean. This can be explained, at least in part, by technological and scientific challenges associated with the collection and interpretation of automated biological data series, and the heavy logistics of biological studies. Yet, biological impacts and ultimate consequences are of utmost concern for society. For this reason, biology and ecosystem research needs to be given priority and we need to address the system as a whole. Predicting ecosystem impacts requires that links are developed between physical and chemical parameters routinely monitored, and incorporated within modeling tools. A focus on integrative models is recommended to improve our ability to anticipate, understand, and adapt to changes in a complex system with multiple feedbacks. These same links can help translate paleo-reconstructions of circulation, productivity and ice cover within the Arctic into analogues for estimating future resource impacts.

4.0 KEY SCIENTIFIC QUESTIONS

4.1 How were past transitions in sea ice connected to energy flows, elemental cycling, biological diversity and productivity, and how do these compare to present and projected shifts?

Sea ice responds to a variety of physical forcing mechanisms that include both dynamic (winds and ocean currents) and thermodynamic (temperature, radiative and turbulent energy fluxes, ocean heat storage) processes (Deser and Teng, 2008). Their interplay results in natural oscillations in the ice-cover that operate on a variety of timescales. Satellite-derived observations of reductions in Arctic summer and winter sea ice cover for the past 3 decades (Serreze et al., 2007, Comiso et al., 2008) can, to some degree, be tied to natural oscillatory phenomena such as the Arctic Oscillation (AO) (Rigor and Wallace, 2004) and the North Atlantic Oscillation (NAO) (Kwok, 2000). However, the continued decline in ice-cover despite the recent change in the mode of these atmospheric circulation patterns (Overland and Wang, 2005) suggests that dynamic and thermodynamic processes associated with long-term warming trends are impacting the sea ice cover in the Arctic (Comiso et al., 2008).

The accelerated reduction in Arctic sea ice captured in instrumental records has recently been shown to correspond to an increase in mean annual summer temperature derived from high latitude lake, ice-core and tree-ring proxy datasets (Kauffman et al., 2009). Critically, this temperature increase diverges from a 2000-year cooling trend that was consistent with diminished solar forcing at high latitudes and further suggests that amplification of greenhouse gas forcing is driving the observed patterns of sea ice retreat (Kaufman et al., 2009; Polyak et al., 2010). These findings support projections for future sea ice extent under elevated CO_2 concentrations, in which the Arctic Ocean may become seasonally ice-free within the next century (IPCC, 2007; Wang and Overland, 2009). However, there remain significant disparities in the modelled patterns of sea ice retreat and those captured in observational records (Comiso et al., 2008; Holland et al., 2006; Barber et al., 2009) that highlight the need for improved physical coupling in existing atmosphere-sea ice-ocean models.

Together with existing Arctic research programs, the ART science framework aims at better understanding the ocean-atmosphere physics that govern the distribution of sea ice, especially with respect to changes that have consequences for productivity, marine organisms and biogeochemical cycling. Accepting that modern observations do not reflect a stable ice regime requires that longer time series are incorporated into the calibration and verification of models used to make future predictions. To understand the coupled atmosphere-sea ice-ocean system, these records must come from the marine sector. Predicting changes to energy flows, carbon and elemental cycling, biodiversity and biological productivity as a response to diminished sea ice cover in the Arctic requires advances in 1) the ability to interpret paleo-records in the most relevant way; 2) improved understanding of the response of the sea ice ecosystem to changing physical forcing mechanisms 3) defining key feedbacks within and between the physical and biological components of the system. The following sub-questions are formulated to address ways to improve coupling between sea ice models and biogeochemical processes.

a) How can the calibration of proxy data from marine sediments be improved through coupling with sea ice models and direct observations?

Proxies derived from marine sediments provide the most continuous archive for sea ice conditions, and large-scale oceanic changes, pre-dating human observations. These proxies are under continued development and include sedimentary tracers of particles entrained and dispersed by sea ice (Darby, 2003; Darby et al., 2009; Krylov et al., 2008) biogenic remains of organisms associated with ice or ice-free conditions (Belt et al., 2007; de Vernal et al., 2008), as well as biological, geochemical and isotopic tracers of brine formation and water mass properties (Bergquist and Blum, 2007; Haley et al., 2008; Hillaire-Marcel and de Vernal, 2008).

Reconstructing the extent of past sea ice is difficult because proxies are only indirectly related to sea ice and require the use of transfer functions having inherent uncertainties (de Vernal et al., 2008). These transfer functions are generally derived from a large regional dataset of surface samples calibrated against observed sea ice conditions, and can in some instances be improved by more comprehensive sampling; linking of laboratory and field-based studies to observations on modern and past microfossil distributions in sediments; and through more statistically rigorous characterization of sea ice concentrations, afforded by sophisticated spatial sea ice models. Improvements to existing calibrations require that we bring together modern processes with paleo-reconstructions and also need to address inter-annual and decadal variability at a level consistent with the temporal resolution of the studied sediments.

In addition to information on past sea ice conditions, marine sediments contain a valuable archive of water mass properties that can be extracted through integrated studies of granulometric, compositional, isotopic and micropaleontological analyses (Slubowska-Woldengen et al., 2007). An improved understanding of how past changes in gateway exchanges and freshwater input has affected regional patterns of sea ice is critical for calibrating and testing sea ice models (Shimada, 2006; Stroeve and Maslowski, 2007). Therefore, proxies for changes in either the position and/or flux of different water-masses need to be explored in regions where the most robust reconstructions of past sea ice conditions exist and along the inflow and outflow shelves. Coupling these records with circulation and sea ice models can help constrain the magnitude and impacts of changing gateway fluxes on circulation and sea ice characteristics.

b) What were the principal forcing mechanisms responsible for regional variations in sea ice cover and biological productivity during past environmental transitions?

Satellite observations of sea ice cover do not provide a robust baseline for defining the natural variability in the atmosphere-sea ice-ocean system as they coincide with an era of anthropogenic driven greenhouse gas forcing. Understanding the natural variability, and the context of observed changes, requires an analysis of longer time series attainable through the analysis of either historical or marine geologic records. For example, the Holocene provides an excellent framework for furthering our understanding on the forcing mechanisms and spatial variability of sea ice by coupling sea ice and paleocirculation proxies from high resolution marine geologic records. These more detailed reconstructions are possible due in part to the facility with which these sediments can be sampled, as well as the abundance of complementary data from terrestrial, lake, ice-core (Kaufman et al., 2009) and marine gateway records (Stein, 2007; Slubowska-Woldengen, 2008) that provide essential boundary conditions for sea ice models and place important constraints on the timing, type and persistence of ice in some regions (England et al., 2008). Coupling these records with sea ice models can help resolve the relative importance of sea-level rise, oceanic (Shimada et al., 2006) and atmospheric forcing (Rigor et al., 2002; Overland and Wang, 2005) on the distribution of sea ice through past environmental transitions. Historical and archaeological studies on changing land-use patterns of native people, and the distribution of fossil mega-fauna (Dyke et al., 1999; Savelle et al., 2000) also provide important historic data that can help identify regions of high productivity and how these relate to past physical forcing mechanisms, and how well they can be reproduced in spatial sea ice models.

Older time intervals, including previous interglacial episodes and earlier periods of global warmth when CO_2 concentrations were naturally elevated (i.e. the Pliocene and Eocene (Pagani et al., 2009; Pearson et al., 2009; Stickley et al., 2009)), are also of great interest to investigate past transitions between perennial, seasonal and ice free conditions. They also provide more direct analogues for projected shifts toward seasonal ice-conditions in the Arctic. Targeting and sampling sediments from these and other past times can provide important constraints on water mass properties, stratification, sea ice cover and either direct or indirect information on the response of biological systems in the Arctic Ocean.

c) How do patterns of sea ice reduction forced by elevated greenhouse gas concentrations differ from those driven by changes in solar or oceanic forcing?

Regional variability in sea ice patterns directly influence the locality where an increase or a decrease in the length of the biological growth season occurs along the pan-Arctic circuit (Arrigo et al., 2008). It is therefore vital to understand the spatial forcing mechanisms and their influence on sea ice variability. The impact on sea ice patterns of atmospheric drivers, ocean currents or sea water properties differs among Arctic regions, an observation that appears true for both modern satellite-derived time series (Francis and Hunter, 2007), and those from paleo-reconstructions. For example, at present, the Amerasian Arctic Ocean is affected by a stronger reduction in sea ice extent and thickness, while the European Arctic sector receives a large amount of sea ice due to an increase in the strength of the Transpolar Drift (Kwok, 2009). However, during the early Holocene thermal maximum, driven largely by solar forcing, both modelling (Vavrus and Harrison, 2003) and sedimentary proxies (de Vernal et al., 2005) point towards more severe and stable ice-conditions in the western Arctic. Hence, reductions in the extent of early Holocene sea ice patterns that arose in response to solar forcing appear different from modern observations associated with greenhouse gas forcing (Comiso et al., 2008; Kauffman et al., 2009; Polyak et al., 2010). Determining whether significant differences exist in modelled patterns of sea ice reduction forced by solar insolation as opposed to those driven by changes in greenhouse gases provides an additional means to address the sensitivity of sea ice distribution to different physical forcing mechanisms.

d) How are transitions in the location and extent of marginal ice zones, leads and polynyas affecting air-sea gas exchange and Arctic Ocean ecosystems, including human populations?

Regional transitions in the spatial extent and thickness of sea ice, amount of summer melt-out, and variability in snow accumulation are critical parameters that alter patterns of radiative transfer, stratification, nutrient supply, all of importance for biological production (Carmack et al., 2006). Increased open water facilitates air-sea interactions with uncertain and opposing feedback mechanisms for water temperature, CO_2 fluxes, volatile organic compounds (VOCs) and aerosol formation. Modified water masses distribution and warmer ocean temperatures are also very likely to alter the cycling and remineralization of organic material. For example, changes in the location and extent of open water areas could impact cloud formation through the release of VOCs by phytoplankton, with a negative feedback on climate warming. In fact, a decrease in Arctic sea ice will have repercussions on the whole global climate system and planetary-scale atmospheric circulation (see Budikova, 2009 for a review).

Moreover, open water areas within ice-covered regions (i.e. leads and polynyas) have been traditionally recognized as important biological/biogeochemical hot spots with active material cycling and high productivity from low trophic levels to top mammal predators (e.g. Stirling, 1997). These relatively small areas compared to ice-covered and seasonal ice zones have been described as marine oasis and important hunting grounds for northern populations (Smith and Barber, 2007 and chapters therein). Transitions in sea ice will change the location, occurrence and extent of leads and polynyas with potentially severe consequences for local communities that are dependent on the use of open water areas surrounded by ice for the harvesting of renewable resources (Laidler et al., 2009). The suite of chemical and physical processes and stressors caused by a shift of the retreating ice edge and transitional ice conditions requires a proper understanding of their interactions and feedbacks. To address the projected impacts on both the magnitude and nature of changes to Arctic marine ecosystems and for the human populations that rely on them, adequate parameterization of biogeochemical and physical variables through integrated modelling efforts is essential.

e) How do transitions in sea ice conditions affect sea ice and ice-associated ecosystems and carbon cycling on Arctic shelves and basins?

Sea ice cover structures Arctic ecosystems in various ways, for example by providing a specialized habitat to a host of species, some of which are unique to the Arctic (e.g. *Ursus maritimus*). The interconnected network of brine pores and channels that forms the sea ice matrix provides colonisation space for the development of sea-ice communities that form the basis of Arctic food webs. Sea ice contains a variety enclosed and semi-enclosed micro-habitats with a range of environmental conditions and different biota and microbial activities (e.g. Deming, 2010). As an example, winter sea ice exposed to temperatures below -20ºC is not permeable to liquids, has less than 1% brine volume and brine salinity well above 200 (Cox and Weeks, 1983). At the same time, the lower part of the sea ice which is in contact with water is near the freezing point and salinity of seawater (-1.8ºC) and is highly permeable. The sea ice matrix is therefore a heterogeneous and dynamic habitat at scales ranging from millimetre to regional, and from diurnal to seasonal and multi-annual. This habitat is undergoing rapid and multidirectional changes. The current shift from multi-year to first-year ice is one example of a key directional change in sea ice habitat and structure with major implications for the sea ice ecosystem.

Sea ice primary production, largely associated with first-year ice in the Arctic, can represent >50% of regional Arctic primary production (e.g., Gosselin et al. 1997). This production plays a key role in Arctic food webs as an early and concentrated food source for zooplankton grazers (Søreide et al., 2010). Overall, the amount and timing of sea ice production depends on a variety of factors including the ice crystallographic structure, availability of light and nutrient supply and regeneration. The composition and diversity of sea ice communities also depends on the incorporation of organisms in the ice at the time of its formation (Riedel et al., 2007). The current Arctic rapid transitions in ice type (from multi-year to first-year), timing of ice formation and melt, together with predictions of increased precipitation and coastal erosion, are all expected to strongly impact sea ice ecosystems with cascading effects throughout Arctic food webs. Currently, it is difficult to predict the response of the sea ice biota to ongoing and predicted changes since complex interactions of physical variables acting at various scales (e.g. ice/snow regimes, ocean temperature, ice microstructure) influence the composition and productivity of sea ice communities. For example, we do not know how a switch from multi-year ice to first-year ice will influence the biodiversity and productivity of sea ice communities and impact on their role in the Arctic global carbon cycling. Even predicting changes in simple physical forcings such as light availability, let alone predicting the effect of these changes, is challenging because of multiple interactions and feedbacks. In this context, it is essential to further our understanding of biogeochemical processes operating within the sea ice and at the sea-ice and ice-ocean interfaces, at various scales. We need to improve our understanding of multi-year and first-year sea ice ecosystems, as well as their role in the cycling of materials in Arctic food webs. Inherent to this is the need for improved methods at characterizing the thickness and extent of seasonal and perennial sea ice (Barber et al., 2009). This will improve our understanding of the dominant scales of variability (e.g. regional and temporal) and is needed to improve models of biogeochemical cycling within the atmosphere-sea ice-ocean interface.

4.2 How will biogeochemical cycling respond to transitions in terrestrial, gateway and shelf-to-basin fluxes?

Over the last decades, the physical changes of the Arctic Ocean environment have been manifested by a modified atmospheric circulation over the Arctic and sub-Arctic regions, changing ice melt- and freezing rates, increased freshwater input to the shelves due to higher riverine discharge, changing carbon, methane, and sediment fluxes due to coastal erosion and permafrost thawing, altering freshwater transport patterns on the shelf seas, and modifications to the inflow of water masses from the Atlantic and Pacific oceans (e.g., Quadfasel et al., 1991; Schauer et al., 2004; Dmitrenko et al., 2008; Polyakov et al., 2008; Steele et al., 2008; Simmonds and Keay, 2009; Shakhova et al., 2010). The repercussions of rapidly changing marine forcing on the coastal environment can be vital for the residents of the Arctic and their activities, as they may affect e.g. transportation routes and cultural infrastructure, traditional harvesting areas, or even entire settlements (Jones et al., 2009). The impacts can also be significant for coastal ecosystems including large river deltas that may be affected by land-loss and changes in the flooding regime and estuaries that are critical habitats for juvenile fish and brackish-water biota. In addition to the intra-Arctic consequences, the alterations of the Arctic coastal and shelf environments may imply considerable effects on global scales, e.g. through feedbacks to atmospheric processes and exchanges with the World's oceans via the oceanic gateways.

The number of environmental observations in the Arctic Ocean is steadily increasing and progress is gradually made in defining the key processes in this complex system. Yet, we are far from understanding many of them, or how they are related to each other. Our knowledge largely built upon observations unevenly distributed in space and time, as large parts of the Arctic are still difficult to access, or even inaccessible during some seasons. Moreover, we have not fully utilized the potential of integrating paleo-records with current physical observations, in order to decipher the physical conditions and rates of change in past times and to model scenarios of the future.

Three sub-questions are formulated to better understand the modifications of the Arctic terrestrial-marine interface during future warming and the associated biogeochemical implications:

a) How will a modified hydrological cycle and changes in coastal physical conditions affect the delivery and transport pathways of fresh water and particulate and dissolved materials across the terrestrial-marine interface?

Over the next century, near-surface permafrost across the circumpolar Arctic is expected to degrade significantly, particularly in land areas south of 70°N (Lawrence et al., 2008). This can result in slope failures along river banks and coasts that border the Arctic Ocean. River discharge and river-ocean interactions are also expected to undergo significant changes as a result of modifications in precipitation, temperature and associated impacts on permafrost and sea ice thickness, extent and duration. Under a CO_2 doubling scenario, annual Arctic river discharge could increase by 10-20%, while winter discharge may increase by as much as 50-80% (ACIA, 2005). It is likely that these scenarios will be accompanied by increased loads of freshwater as well as suspended and dissolved organic and inorganic matter to the Arctic marine ecosystem. The export of turbid waters from rivers and coastal regions could enhance the delivery of nutrients to micro-algal populations, but could also impair photosynthesis by shading solar irradiance (Retamal et al., 2008). In addition, increased freshwater supply could strengthen stratification offshore, thus impeding further the upward renewal of nutrients during winter, especially in river-influenced shelf ecosystems (e.g. Lavoie et al., 2009). Further investigation of these observations is required to understand the influence of increased turbidity and fresh-water contents on the ecosystem and to identify the potential consequences for animal life and society.

Coastal processes are intensified during certain parts of the year when sea ice cover is less extensive or non-existent. Larger areas of open water, and hence increased fetch, can result in larger waves and stronger forces acting on shorefaces, backshore bluffs and beaches, thereby generating both rapid recession and reworking of near-shore materials. Compounds contained by the permafrost are released during thaw and erosion and subsequently dispersed in streams, lakes, and coastal waters.

Given the widespread impacts of permafrost thaw and enhanced riverine delivery, it is essential to monitor the loads of inorganic and organic material at the mouths of the pan-Arctic rivers as well as in the near-shore and inner-shelf zone during current environmental transitions. In addition, remote sensing imagery could be of particular interest to trace the spatial and temporal variability of land-derived supplies through the continued development of algorithms to measure and differentiate terrestrial and marine signals in the Arctic environment.

b) How does the transition to warmer climate affect the lateral and vertical distribution of water masses in the Arctic Ocean and what is the potential impact on the ecosystems of the continental shelves?

In a warming climate the lateral extent and vertical distribution of the water masses in the Arctic Ocean may be modified with particularly large impacts on the shelves and shelf slopes.

Here, even minor shifts in strength and vertical redistribution could result in a substantial reorganization of the oceanography with significant consequences for the ecosystem and the near-coast societies.

During the last decades, warming events at intermediate water depths occurred through the enhanced inflow of Atlantic water. The first observations were made during the 1990s (Quadfasel et al., 1991), while a second pulse was measured in the early 2000s (Schauer et al., 2004; Polyakov et al., 2004). This latter pulse reached the Siberian continental margin after six years showing that the warm signals indeed reach far into the Arctic Ocean (Dmitrenko et al., 2008). Recent observations of increased heat flux have also been made in the western Arctic for the inflow of Alaskan Coastal water through the Bering Strait (Woodgate et al., 2006). The intrusions of warm water masses further into the Arctic will likely favor the northward migration of more temperate species. The general increase in Atlantic Water inflow has already resulted in the reappearance of e.g. the blue mussel *Mytilus edulis* in fjords on Svalbard, after 1000 years of absence (Berge et al., 2005). In order to estimate the impact on the habitable zones for the Arctic organisms we need to better understand – for both past and modern times - the mechanisms behind the inflows through the Arctic gateways, to resolve the time-scales of their variability in strength as well as location, and to understand the spatial reach of the predicted modifications (cf. Hu et al., 2010).

The upper 100-200 m of the Arctic Ocean are fed by low-saline waters originating largely from the freshwater river runoff and/or inflow from the Pacific Ocean, while the intermediate depths (150-900 m) are occupied by the relatively warm and saline Atlantic Water. Will this vertical distribution of the water masses remain the same throughout the ongoing transition, or in a future state of a warmer climate? Microfauna in sediment records from the Last Interglacial (128,000 – 115,000 yrs BP) indicate that Atlantic Water may have been present at much shallower depths on the Beaufort Shelf than at present, suggesting a different vertical extent of Atlantic Water and maybe even an unstratified Arctic Ocean during that time (Brigham-Grette and Hopkins, 1995). What were the properties and the distributions of water masses during past warm times, and how did they change in space and time? Do observations from the past constitute possible durable scenarios resembling a warmer future climate? Dedicated efforts integrating paleo-reconstructions, monitoring of the present state, and simulations of future conditions are essential for investigating the implications of a modified vertical distribution for the ecosystem functioning as well as for identifying the regions most susceptible to such changes.

c) How are the shelf-basin exchanges affected by ongoing alterations of the Arctic environment?

The shelf-basin exchange of water is believed to take place through a variety of mechanisms. Among these are eddies observed to be spawned off from meandering shelf-break currents (Spall et al., 2008) providing the means for transporting shelf-waters and entrained hydrographic characteristics. Such eddies are found in both the Canada and the Eurasian basins (Timmermans et al., 2008; Woodgate et al., 2001) and are thought to contribute significantly to the offshore transport of heat, salt and particulate matter, as well as supporting high primary production and affecting the deep-basin food webs (Tremblay et al., 2008, Grebmeier et al., 2009 and references therein). In addition, cascading plumes of dense waters, produced on the shelves during sea-ice formation are believed to help maintain the halocline, provide an offshelf source of nutrients, and ventilate the interior of the Arctic Ocean (Aagaard et al., 1981; Muench et al., 2000). Other important processes of the shelf-basin exchange are the wind-induced upwelling/downwelling events which, at sites, seem to occur frequently and either lift the nutrient-rich Atlantic water up to relatively shallow depths on the shelves and shelf slopes (Pickart et al., 2009) or transport down organic matter to the deep-basin benthic communities.

The complete life cycle of shelf-break eddies, as well as their frequency, intensity and spatial variability, are still not fully understood. The shelf-water plumes into the deep basins depend on the seasonal modifications of water masses and sea ice formation but our current knowledge of this mechanism is mainly restricted to the seasons and conditions met during dedicated field campaigns. The spatial range and duration of the upwelling/downwelling events, as well as their implications for the normal water circulation are yet to be fully investigated. Therefore, modeling and extended monitoring efforts are prerequisites for linking these processes to each other, to evaluate their ongoing transitions and their relevance for the ecosystem.

4.3 How do Arctic Ocean organisms and ecosystems respond to transitions in environmental conditions including temperature, stratification, ice conditions, and pH?

Transitions in environmental conditions, such as changes in sea ice distribution and thickness, snow conditions, atmospheric forcing, temperature regimes, freshwater supply and CO_2 concentration, are all projected to change organisms currently living in the Arctic (ACIA 2005). Issues related to ecosystem response are important for the societies living in or outside the Arctic region, and for the ecosystems themselves. However, these biological changes are difficult to predict. Among the many challenges we have in order to understand and predict changes are the lack of sufficient understanding of how the present ecosystems function, the heterogeneity within the Arctic regions, the individual response of different species to changes, and how those changes will influence ecosystem interactions and food web transfers. The challenges to our understanding of biological changes include evaluating function, interactions and productivity of organisms ranging from virus and bacteria, benthic and pelagic uni- or multicellular species, to the impacts on harvestable resources or higher trophic predators like fish, marine mammals or seabirds. There is an obvious need to strengthen observations and combine them with experiments and models to grasp the complexity of Arctic ecosystems and their response to changes.

Five high-level sub-questions were formulated in order to develop a system-level scientific program to evaluate the biological impacts of projected environmental changes:

a) Are there regional differences in how primary production is responding to changes in physical drivers across the Arctic?

The controlling and limiting factors of primary production like irradiance and nutrient supply vary within the different Arctic or sub-Arctic regions (Mueter et al., 2009; Tremblay and Gagnon, 2009). Regional ecosystems are expected to change with environmental conditions such as seasonal ice cover, stratification and vertical mixing related to melting, freshwater input, turbidity, or wind regimes. How these changes will differ regionally is expected to be related to the function and nature of each Arctic sub-region (Carmack and Wassmann, 2006). Hence, future changes in the magnitude and nature of primary production should reflect compounding effects of spatial heterogeneity in environmental changes and ecosystems. For example, strong emphasis has been given to the increase in primary production in the Amerasian Arctic during the record low ice extent in 2007, while less so to the simultaneous decrease of primary production in the European sector (Arrigo et al., 2008). A trend toward small algae appears to be driven by freshening of the surface layer (Li et al., 2009) with potentially strong regional implications for the fate of production and biogeochemical cycling. Ice edge retreat off the shelf edge can in certain regions induce upwelling of nutrient-rich water increasing production in previously low-productive areas (Carmack and Chapman, 2003). Hence, there is a need to identify the present constraints and potential changes to better understand and predict how primary production will respond in each of the Arctic sub-regions.

b) What are the tolerance limits of key organisms[1] and how do changes in environmental conditions affect the composition and structure of Arctic food webs, and what are the consequences for productivity and harvestable resources?

The survival and reproductive success of organisms is a response to how well they are adapted to a given set of conditions, e.g. temperature, salinity, nutrient, pH, oxygen, which is ultimately driven by variability and changes in the physical system (Drinkwater et al., 2010). When one or more of these forcing factors change, there is potential for sub-optimal conditions in the physical environment (e.g. loss of sea ice, changes in water mass properties) or biological interactions (e.g. increased competition between species, decreased food availability, increased predation). Presently, there is a wide gap in knowledge with respect to the tolerance limits of many organisms at different stages of their life cycle. Even for simple forcings like temperature, we know little about the range where key species are able to grow and reproduce. The sensitivity and dependability of key species to timing in onset of the productive season, or the location of productive areas is also largely unknown. Furthermore, we do not know the response to combined effects (e.g. temperature, competition and/or pH), nor the impact of a species shift, for the food web structure and energy flow. Complex interactions between bottom-up (e.g. type of primary producers) and top-down (e.g. predator-prey connections) determine how energy and carbon flow in the food web, i.e. how it functions. The trajectory of marine food web functionality under current environmental transitions is a critical issue. For example, Arctic food webs may experience a dramatic shift if a key species that provides a major energy link in the trophic network is removed or replaced. This could negatively impact the production and function of a variety of organisms ranging from plankton to apex predators, as well as the Arctic residents that rely on fisheries or marine mammal resources for food or economic growth (Hovelsrud et al., 2008). Because of the advective nature of the Arctic Ocean, ecosystems are exposed to new species continuously (e.g. Reid et al., 2007; Berline et al., 2008; Hegseth and Sundfjord, 2008), and the composition of Arctic food webs reflects the present success of each species. There is thus potential for transient or more permanent changes in the structure and function of Arctic food webs (*sensu* Carmack and Wassmann, 2006). Since it is also difficult to study an entire food web, field researchers and modellers should direct their work toward key species that constitute a vital link of energy, nutrient or organic matter in the ecosystem.

[1] Key organisms mean important predators or prey, with higher ecological impact than their relative biomass or abundance indicates (expanded from Paines (1969) keystone species).

c) What are the controls on the spatial and temporal variability of pelagic-benthic interactions, and how do these influence biogeochemical cycling in different Arctic regions?

Primary production supports ecosystems by providing the energy base, while pelagic consumers largely determine the distribution of this energy within the ecosystem through phytoplankton grazing. Overall, a combination of physical and biological factors such as temperature, water depth, size and type of primary producers, the activity of the microbial food web (remineralization), the abundance and type of pelagic grazers, all conspire to influence the fate of primary production and pelagic-benthic interactions in Arctic ecosystems. However, our knowledge of how autotrophs and heterotrophs regulate the pathways of carbon and nutrient flow and affect the stoichiometry of biogenic matter in the Arctic is scarce for many regions (Macdonald et al., 2010). For example, mismatch between micro-algal blooms and zooplankton grazing on inflow shelf seas of the Arctic Ocean (i.e. Barents and Chukchi seas) can lead to high export production to the sediments, facilitating a rich, benthic ecosystem (e.g. Dunton et al., 2005; Tamelander et al., 2008). On these shelves, warming waters and the northward advance of more temperate species could destabilize the benthos-oriented productivity regime with more biomass being retained in the pelagic environment (e.g. Grebmeier et al., 2006). Similarly, high sinking export of organic matter and a tight pelagic-benthic coupling is often associated with productive marginal ice zones or with spring melt of first year ice on shelves (e.g. Juul-Pedersen et al., 2008; Tamelander et al., 2008). However, in areas such as in the East-Siberian Sea and along the western Canadian Archipelago, there are simply no sufficient dataset to describe how the system works in terms of retention *versus* export food chains (*sensu* Wassmann, 1998). So how is it possible to adequately understand ecosystem changes if baseline studies are even inexistent for various Arctic regions? In addition, environmental transitions may directly affect the relative timing of food requirement and availability for pelagic consumers such as copepods (Bluhm and Gradinger, 2008). Shifts in the feeding and excretions activities of these consumers could impact how much particulate material is transferred to the microbial loop (e.g. Møller, 2005), which in turn fuels microzooplankton communities and plays a crucial role in biogeochemical cycling (Fenchel, 2008). Arctic heterotrophic populations will be further affected by a likely replacement of the so-called endemic species with the intrusion of less nutritional subarctic/boreal congeners. Therefore, it is urgent to set priorities for future investigations of the biological factors affecting pelagic-benthic interactions in Arctic ecosystems, including type, timing and variability in primary producers, bacterio-, microzoo- and mesozooplankton. This includes studies to determine estimates of depth-specific biomass, as well as feeding, growth, and respiration rates of these consumers under the predominant temperature and food conditions across Arctic regions. Physical factors contributing to the heterogeneity of the different Arctic regions, like depth, advection and water mass distribution, physical mixing or stratification influencing nutrient supply and down-welling of organic matter as well as ice dynamics, are also of great importance as they influence productivity and pelagic benthic interactions through bottom up processes.

d) How can changes in distribution and abundance of higher trophic level species and increased human presence in the Arctic induce trophic cascades in the ecosystems?

Cascading effects, where changes on one trophic level have consequences for higher and/or lower trophic levels, are well known in freshwater systems (Carpenter et al., 1996), but more difficult to detect and observe in marine systems. For example, the decline of large fish stocks induced by high fishing pressure can result in an increased biomass of crustaceans and small fishes, which could in turn promote enhanced predation on mesozooplankton and thus less grazing on phytoplankton (Scheffer et al., 2005). Hence, given the intense fisheries that occur in subarctic regions and that the border between the sub-Arctic and the Arctic is increasingly blurred with climate warming (Nihoul and Kostianoy, 2009), it is most probable that fishing-related cascading effects may be transferred up to Arctic ecosystems. Expanding trawling activities further north as fish stocks migrate, will have consequences on the so far undisturbed benthic communities and benthic feeding organisms. Climatic changes are also expected to induce predator-prey trophic cascades as a response to changed distribution and survival of marine mammal species (see Moore and Huntington 2008, for a review). It is very likely that such cascading effects will influence Arctic ecosystems as human activity, both subsistence and commercial, will also stress large marine species, or as top predator regimes change resulting from changing climate. For instance, a persistent sea ice melt in the Arctic is hypothesised to increase killer whale populations that could replace polar bears as the dominant marine mammal predator (Higdon and Ferguson, 2009). Effects on the Arctic megafauna are often easier to detect than in fish and plankton communities, and can provide important indicators of ecosystem regime shifts and changes in other food web components (Baum and Worm, 2009). Therefore, during the present transitions in the Arctic, it is critical to monitor higher trophic level communities and how they impact the top down control of ecosystem functionality.

e) How will changes in the functioning of food webs impact net heterotrophic/autotrophic processes and will they shift the source/sink potential for atmospheric CO_2 in the Arctic?

The current paradigm is that the Arctic Ocean is a net sink for atmospheric CO_2 partly due to high rates of primary production on the continental shelves and under-saturated surface waters in the central basins, caused by perennial ice cover (Bates and Mathis, 2009). However, an important fraction of planktonic communities in the Arctic Ocean already appears to be net heterotrophic due to elevated zooplankton biomass (Olli et al., 2007) or high allochtonous inputs (e.g. Garneau et al., 2008; Regaudie-de-Gioux and Duarte, 2010). Additionally, increases in sea temperature and in fluxes of organic matter from enhanced primary production and thawing terrestrial environments are expected to result in increased plankton respiration (Kirchman et al., 2009). Recent experimental results within the relevant temperature range (-2 to +5˚C) suggest that plankton community respiration will exceed increase in primary production (Vaquer-Sunyer et al., 2010). Hence, the role of Arctic plankton communities as CO_2 sinks is expected to weaken in the future and become CO_2 sources with warming predicted for the 21st century. As the reduction of sea ice continues to expose the central Arctic basin, equilibration of surface waters with the atmosphere will also begin to occur. Despite large unknown feedbacks in the dynamics of the oceanic system, it is likely that the sink for atmospheric CO_2 in the Arctic will increase on short timescales, but that this trend could reverse rapidly as basin waters become saturated with CO_2 and rates of remineralization increase. These critical transitions could have a major impact on the long-term sink for atmospheric carbon as sequestration and burial on the continental margins and in the deep Arctic basins would likely decrease.

5.0 INTEGRATED APPROACH

To better define, synthesize and integrate the linkages between physical drivers, biogeochemical cycles, and biological production four pillars are defined in ART: (i) process studies and observations to reveal mechanisms, (ii) establishment of links to existing observations and ongoing monitoring programs, (iii) evaluation, synthesis and integration of geological records to extend time-series, and (iv) modeling to improve our understanding and predictive capabilities of climate-induced transitions. ART recognizes the value of both conceptual and numerical models as powerful tools to help frame and evaluate new questions, observations and strategies. As such, modeling should not be the end-product of ART, but should be included throughout the implementation process (Figure 4).

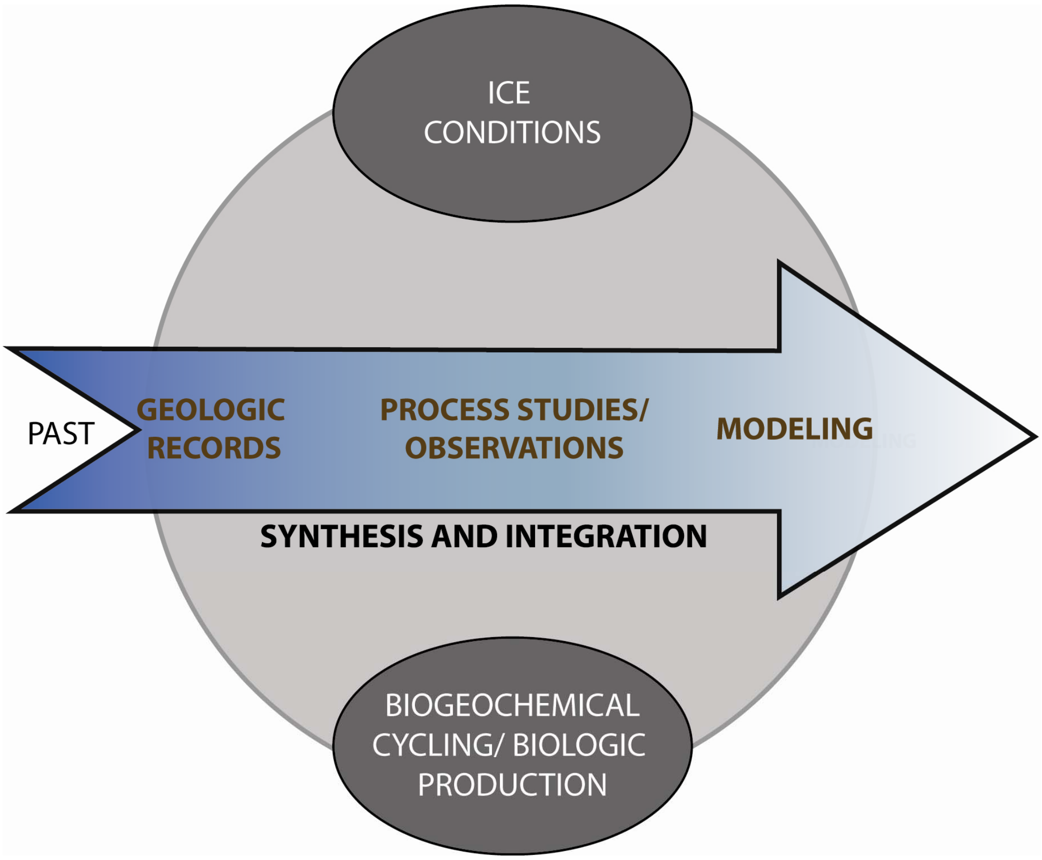

Figure 4: Schematics representing the conceptual approach to address the multidisciplinary challenges of the Arctic in Rapid Transition.

Integrating the established and proposed monitoring programs in the Arctic is an important aspect of ART, as they continue to deliver the most up-to-date and comprehensive data available for assessing ongoing change. Within ART, a multidisciplinary, synchronous pan-Arctic approach with standardized measurement and analytical techniques is required to meet the challenge of evaluating the increasingly dynamic scenarios of the Arctic Ocean in states of transition. ART recognizes that additional technological developments are needed for autonomous and event-driven sampling methods, for biogeochemical sensors, and for Autonomous Underwater Vehicles (AUVs) adapted to the Arctic Ocean environment (deep and shallow water environments). Data collection and transmission from moored observatories as well as from AUVs is especially challenging in the Arctic Ocean due to the presence of ice, and new technological developments are urgently needed. To that effect, cabled seafloor observatories, e.g. in the Fram and Bering Straits, can free long-term (moored) observatories from the challenges of overlying surface constraints due to sea ice and weather conditions

However, as recognized in the ICARP II Science Plans, ocean monitoring is impoverished without the long-timescale records available from paleoceanography and the boundary conditions that can be obtained from marine geology and geophysics. The past and the present are the key to our ability to predict the future. Defining change and identifying transitional states in the Arctic requires geologic and historic records to adequately define natural variability of the system. Paleo-reconstructions of the Arctic during past warm periods provide basic analogues, defining what we can expect in the immediate and long-term future, and provide a tool for investigating the influence of changing boundary conditions on the development and persistence of sea ice (Figure 5).

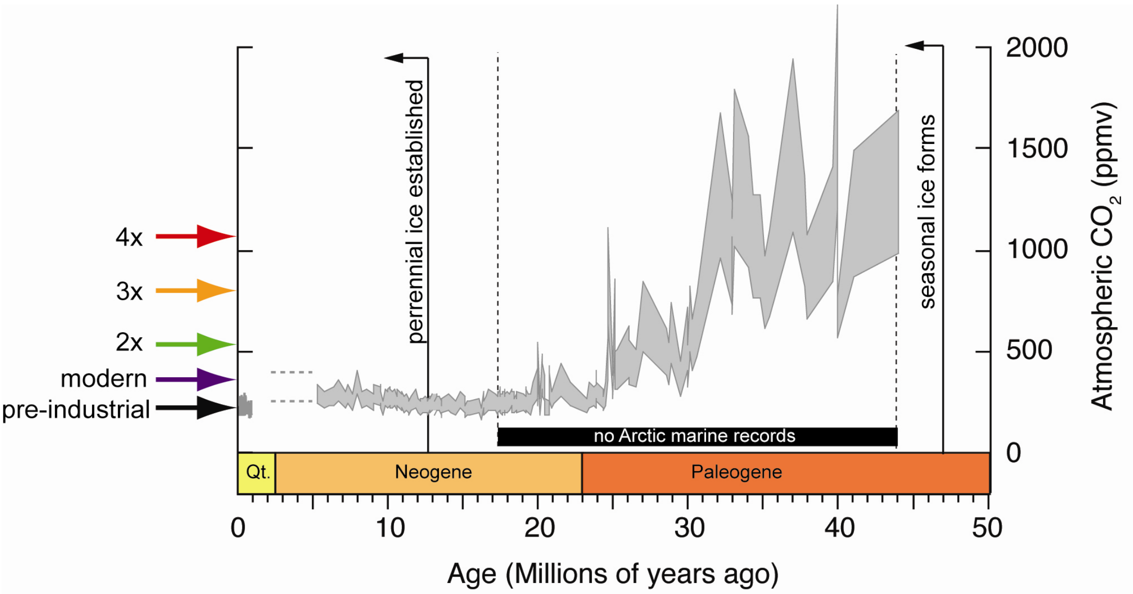

Figure 5. Cenozoic reconstruction of atmospheric carbon dioxide concentration from marine proxy (Pagani et al., 2005) and ice core data. Results from the Arctic Coring Expedition on the Lomonosov Ridge indicate that seasonal sea ice was established around 47 Ma, when greenhouse gas concentrations were comparable to levels at 2-4x the modern (arrows on left). Indications of perrennial ice are first reported at ~12-14 Ma (Polyak et al., in press), with possible periods of seasonal ice returning during warm intervals in the Quaternary (Qt.) and Neogene.

6.0 NEXT STEPS

After the successful presentation of the ART Draft Science Plan to the AOSB during the Arctic Science Summit Week 2010 in Nuuk, ART was approved by the AOSB. The Draft Science Plan will be presented to the larger scientific community both at conferences (IPY-Oslo, AGU. Arctic Frontiers, ASLO, ASSW 2011) and it will be published on the AOSB webpage and comments will be asked through Arctic list servers and mailing lists. In order to develop the implementation plan an ART Implementation Workshop, endorsed by the AOSB, is proposed at the Freshwater Institute in Winnipeg, Canada for October 18-20, 2010.

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APPENDIX I: ART INITIATION WORKSHOP MEETING REPORT

The proposed program entitled "Arctic in Rapid Transition" (ART) is an initiative of the Arctic Ocean Sciences Board: the Marine Scientific Standing Committee of the International Arctic Science Committee. During the March 2009 meeting of the AOSB, the Board directed the ART steering group (SG), comprised almost exclusively of early career scientists, to organize a workshop to begin the process of developing a science and implementation plan for ART.

On 7-9 November, the ART Initiation Workshop was held in Fairbanks, Alaska. Fifty-eight scientists from nine countries participated in the workshop which was hosted by the International Arctic Research Center at the University of Fairbanks. The workshop was sponsored by AOSB/IASC, the US NSF, the Norwegian Research Council, the Department of Fisheries and Oceans Canada, the Association of Polar Early Career Scientists, and IFM-GEOMAR.

The workshop was unique in that it was entirely planned by early career scientists and over half of the participants were early career scientists or students. Participants were asked to prepare a one-page summary of what they viewed to be the most critical question of those posed in the ART white paper which can be found at www.aosb/art.
The workshop began with six keynote speakers from various disciplines. (Agenda attached) These presentations helped put ART in the context of ongoing research in the Arctic and set the stage for the working group meetings that took place for most of the first and second days.

The meeting was organized around seven key questions posed in the white paper. Each working group reviewed the question, discussed whether or not it was the right question in light of our current knowledge about the arctic and then discussed how to go about answering the question.
The final day of the workshop was spent in plenary. Each working group reported to the full workshop on the results of their discussions. This resulted in a further narrowing of the critical questions into three main questions centered around sea ice, land-ocean interactions, and ecosystem responses. These questions are:

A. How do recent spatial and temporal transitions in sea ice extent and thickness compare to those in past and projected climates, and what are the influences on and feedbacks from energy flows, carbon cycling and biological productivity?

B. How will biogeochemical cycling respond to transitions in terrestrial, gateway, and shelf-to-basin fluxes and what are the consequences for socio-economic activities?

C. How do ecosystems respond and feedback to changes in temperature, vertical stratification, seasonal ice zones, and acidification associated with current environmental transitions?

Because of the large number of early career scientists attending the workshop, an expert panel was convened to talk about the process of taking an idea like ART from concept to science and implementation plan and then to the proposal stage. Six experts shared their views on

how this is best done and have offered to continue to provide support to the early career SG as they write the science and implementation plan.
In addition, the workshop included a ½ day field trip to learn more about the impact of climate change in Alaskan permafrost. The fieldtrip was led by Dr. Kenji Yoshikawa from UAF.

The SG met for one full day after the conclusion of the workshop to refine the key scientific questions, to develop an outline for a science plan, and to develop a timeline to complete the science plan by the time of the AOSB meeting in Nuuk Greenland in April 2010. The outline they developed is attached.

The SG is grateful to the sponsors of the workshop for their support in bringing so many high quality expert scientists and numerous early career scientists to Fairbanks. The exchanges that took place will help to shape the final science plan. The SG intends to continue to interact with workshop participants to receive their feedback and ideas as the science plan takes shape.

APPENDIX II: ART-RELEVANT PROGRAMS

Program/project	(Selected) main goal(s)	Web address	Duration
ACD – Arctic Coastal Dynamics	- Multi-disciplinary and multi-national forum to exchange ideas and information. The overall objective is to improve the understanding of circum-Arctic coastal dynamics as a function of environmental forcing, coastal geology, cryology and morphodynamic behavior.	http://web.arcticportal.org/acd	2006-2011
APEX – Arctic Palaeoclimate and its Extremes	- Network research programme aiming to understand Arctic climatic changes beyond instrumental records.	http://www.apex.geo.su.se/index.php	2007-
SBI – Arctic Shelf Basin Interaction – Phase III	- The essential aim of SBI Phase III is the integration and synthesis of SBI Phase I and II results with those of other projects into pan-arctic and global models in order to improve the understanding of the Arctic system as a whole.	http://www.eol.ucar.edu/projects/sbi/Phase3abstracts.html	2007-2010
ArcticNet	- Contribute to the development and dissemination of the knowledge needed to formulate adaptation strategies and national policies to help Canadians face the impacts and opportunities of climate change and globalization in the Arctic.	http://www.arcticnet.ulaval.ca/	2004-
ARCTOS – Arctic marine ecosystem research network	- Researchers network of Arctic marine ecologists in northern Norway and Spitsbergen across institutions, with close pan-Arctic collaboration. Collaborate on research projects, PhD school, applied science, and infrastructure.	http://www.arctosresearch.net/	2002-
ATP – Arctic Tipping Points	- To identify the elements of the Arctic marine ecosystem likely to show abrupt changes in response to climate change, and to establish the levels of the corresponding climate drivers inducing regime shift in those tipping elements. State-of-the-art oceanographic, ecological, fisheries, and economic models will determine the effect of crossing those thresholds for the Arctic marine ecosystems, and the associated risks and opportunities for economic activities dependent on the marine ecosystem of the European Arctic.	http://www.eu-atp.org/	2009-2011
BEST – Bering Ecosystem Study	- To develop an end-to-end mechanistic understanding of how climate change will affect the marine ecosystems of the eastern Bering Sea, the continued use of their resources, and the social, economic and cultural sustainability of the people who depend on them.	http://www.fish.washington.edu/research/best/	2003-
BIOTA (Biological Impacts of Trends in the Arctic)	- To assess the impacts of climate-associated changes on the productivity, biological diversity and biochemical cycling in sea ice Arctic ecosystems.	Not available yet	2009-
C3O – Canada 3 Oceans	- To observe North Pacific, Arctic, and North Atlantic waters, and establish a scientific basis for sustainable, long-term		2007-2009

	monitoring.		
CFL – Circumpolar Flaw Lead System Study	- To contrast and compare the early opening (late closing) of the flaw lead area against that of the adjacent fast ice (southern Beaufort Sea). This contrast will focus on the oceanic and atmospheric forcing of the ice cover in these two regions and describe how these physical processes moderate biogeochemical processes within the Arctic marine ecosystem.	http://www.ipy-cfl.ca/	2007-2011
DAMOCLES – Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies	- Observing, understanding and quantifying climate changes in the Arctic.	http://www.damocles-eu.org/index.shtml	2006-
ESSAS – Ecosystem studies of sub-Arctic Seas	- To compare, quantify and predict the impact of climate variability and global change on the productivity and sustainability of Sub-Arctic marine ecosystems.	http://web.pml.ac.uk/globec/structure/regional/essas/essas.htm	2003-
iAOOS – integrated Arctic Ocean Observing System	- Not a funded programme in its own right but a pan-Arctic framework designed to achieve optimal coordination of funded projects during the IPY. Its main concern is with Arctic change, including all aspects of the role of the Northern Seas in Climate, and it draws its primary focus on the present state and future fate of the Arctic Ocean perennial sea ice.	http://www.aosb.org/programs.html	2007-
ICE-ECO – Comparative studies of ice-associated ecosystems in changing Arctic shelf seas	- Pan-Arctic research project on the impacts of changing environmental conditions, especially the change, both in time and space, of the seasonal and perennial sea ice conditions, on the functioning and productivity of marine ice-associated ecosystems on Arctic marginal shelf seas (in planning).	Not yet available	2009 -
ISAC – International Study of Arctic Change	- Open-ended international research program designed to understand the future state of the Arctic System under anthropogenic stress. The driving force behind ISAC is the need to build understanding, improve capacity for predicting Arctic System changes, and develop necessary mitigation and adaptation strategies to minimize the adverse effects of such changes.	http://www.arcticchange.org/	2003-
LOICZ – Land Ocean Interactions in the Coastal Zone	- Investigating changes in the biology, chemistry and physics of the coastal zone. Since 2003, LOICZ has expanded its areas of research to include social, political and economic sciences in order to address the human dimensions of the coastal zone.	http://www.loicz.org/about_us/index.html.en	1993-
NABOS – Nansen and Amundsen Basins Observational System	- To provide a quantitative observationally based assessment of circulation, water mass transformations, and transformation mechanisms in the Eurasian (NABOS) and Canadian (CABOS) Basins of the	http://nabos.iarc.uaf.edu/objectives.php	2002-2009

	Arctic Ocean.		
SAON – sustained Arctic Observing Network	- Process to further multinational engagement in developing sustained and coordinated pan-Arctic observing and data sharing systems that serve societal needs, particularly related to environmental, social, economic and cultural issues.	http://www.arcticobserving.org/	2007-
SciencePub – Arctic Natural Climate and Environmental Changes and Human Adaptation: SciencePub – From Science to Public Awareness	- Advance the understanding of human adaptation strategies to past rapid and large-scale changes in the physical environment following the decay of the last ice-sheet starting 15 000 years ago - Generate public outreach strategies that will leave a lasting legacy of increased public awareness of the natural environmental systems of Arctic	http://www.ngu.no/sciencepub/eng/	2007-2010
SEARCH – Study of Environmental Arctic Change	- Understand the nature, extent, and future development of the system-scale change presently seen in the Arctic	http://www.arcus.org/search/index.php	Mid 1990-
WARMPAST – Arctic Ocean Warming in the Past	- Advance the knowledge of climate warming in the Arctic by studying past climate change, in particular periods during which the climate was instable and reached warmer conditions than today	http://ipy.arcticportal.org/projects/itemlist/tag/Arctic?start=100	2006-
Past4Future	- Work with paleoscience archives to understand the climate system and the importance of predicting future climate changes.	http://www.past4future.eu/	2010-
SIOS – Svalbard Integrated Arctic Earth Observing System	- Establish an (Arctic) Earth System Observing Facility in and around Svalbard that covers meteorological, geophysical, hydrological, cryospheric, and biological processes from a set of platforms to match Earth System Models.	http://www.forskningsradet.no/servlet/Satellite?c=Page&pagename=sios%2FHovedsidemal&p=1234130481072&cid=1234130481072	not started yet
PAM-ARCMIP – Pan-Arctic Measurements and Arctic Regional climate model simulations	- Provide a unique snapshot of trace gases and aerosol distributions, meteorological conditions, and sea ice distribution in the inner Arctic.	http://www.espo.nasa.gov/oib/docs/PANARCMIP-V2-20090219.pdf	2009-
CASE ITN – The Changing Arctic and Subarctic Environment	- Research and training programme on marine biotic indicators of recent climate changes in the high latitudes of the north Atlantic	http://caseitn.epoc.u-bordeaux1.fr/	2010-2014