International Arctic Polynya Program (IAPP)

New Mission Statement:

Polynyas in the Arctic's Changing Environment (PACE)

Prepared by
IAPP Scientific Coordinating Group (SCG; see Appendix I)

Purpose of this document

The original Terms of Reference for the International Arctic Polynya Program (IAPP) were produced as part of a "Mission Statement" in January 1991, at a time when basic knowledge of Arctic polynyas was minimal and of a disciplinary nature. The interdisciplinary knowledge base on Arctic polynyas has changed markedly since then, as a result of IAPP initiatives, just as the Arctic environment itself has undergone significant change. Accordingly, this document puts forward a new Mission Statement for the IAPP that builds upon the past (the study of individual polynyas in series) and embraces the challenges of the future (how to study polynyas in parallel on a decadal time frame). It provides a blueprint of guiding principles and core parameters that can be pursued and shaped further during national and international workshops and science planning efforts for the future.

Summary

More than a decade of international efforts under the auspices of the IAPP has resulted in two large and very successful multi-disciplinary studies of major Arctic polynyas. Both have addressed hypothesized couplings between physics, chemistry and biology, with an emphasis on the resulting polynya ecosystem and various fluxes (of water, ice, heat, carbon, other elements, gases, and life) to and from it. The Northeast Water, which forms off the NE coast of Greenland (77–81°N), was studied intensively from ice camps and the icebreakers *Polarstern* (Germany) and *Polar Sea* (USA) in 1991–1993. The North Water, which forms in northern Baffin Bay between Greenland and Canada's Ellesmere Island (76–79°N), received equally if not more intensive study in 1997–1999 from ice camps and the icebreakers *Louis S. St. Laurent* and *Pierre Radisson* (Canada). The rich comparative database developed from these first two IAPP studies has vastly expanded previous knowledge of these areas. The results have been essential to identifying key features that determine whether a polynya ecosystem is rich or poor in overall productivity, able or not to support top predators, including native peoples. In particular, the International North Water Polynya Study (NOW) identified forcing factors (climatic and oceanic) that generate and sustain the high-magnitude phytoplankton bloom from April to October, an exceptionally long period of production at these latitudes. A remarkably tight coupling between this bloom and higher trophic levels, enabled by early recruitment of zooplankton (essential prey for fish, birds, mammals), helps to account for the North Water being one of the richest ecosystems in the high Arctic and rivaling other highly productive

regions of the global ocean. In the less productive Northeast Water ecosystem, results of the International Northeast Water Polynya Study (NEW) showed that primary production was often decoupled from secondary production in time and space by the particular physical conditions on the East Greenland continental shelf.

The international community is currently engaged in a third IAPP-initiated study, this time of the Cape Bathurst Polynya (70–72°N) and surrounding region where it forms on the Mackenzie Shelf of Western Canada. The larger Canadian-led project, the Canadian Arctic Shelf Exchange Study (CASES, 2002-2005), enabling this polynya study is patterned after NEW and NOW in terms of its high degree of multidisciplinary and international coordination. It builds upon the scientific and logistical experiences from both prior studies. For example, results from NOW emphasized the critical importance of climatic and ice conditions even distant from site to ecosystem function within the polynya. Strengthening the climate, sea-ice and modeling teams is the CASES answer to this reality. NEW results implied the importance of wintertime storms in freshening nutrient conditions for the spring bloom, yet winter moorings of current meters and sediment traps were insufficient to resolve the issue or the subsequent limited ecosystem response. Overwintering a ship for continued multi-disciplinary research through all seasons is the CASES answer to this problem (and to many newly posed questions). This third IAPP study is thus unique in undertaking a year-long sampling plan between two of its seasonally repeated (fall) expeditions. The newly renovated and science-dedicated icebreaker, *Amundsen* (Canada), is currently frozen into Franklin Bay (December 2003 to present), which lies at the southern boundary of the polynya and the entrance to the Northwest Passage through the Canadian Archipelago. Sampling is possible and ongoing, for the first time, throughout the open and closed seasons of a polynya.

The base of knowledge and discoveries emergent from NEW, NOW and soon CASES derives in large part from well-orchestrated, multi-year field programs and repeated sampling in key areas, always drawing on the cumulative resources of multiple nations. These scientific and logistical successes have led the Science Coordinating Group (SCG) of the IAPP (see Appendix I) to develop a new approach to future polynya research under the auspices of what we call PACE — Polynyas in the Arctic's Changing Environment. Under PACE, the research community shifts from studying polynyas in series to studying them in parallel, with long-term, well-paced time-series work to provide a solid basis for identifying environmental change, responses and feedbacks, and possible future scenarios, especially at the ecosystem level. Ideally, such work would go forward on a decadal time frame in a pan-Arctic sense, including simultaneous study of the Cape Bathurst Polynya, North Water, Northeast Water, Svalbard polynyas (especially the Storfjorden), and the Laptev and Kara Sea polynyas on the Russian continental shelf. Practical considerations must figure in such ambitious planning, including the cost of logistics, the challenges of gaining clearance to Russian waters, and the mobilization of sufficient talent. We continue to aim high, given major new funding decisions by the Canadian government, recent German and North American successes in developing Russian collaborations, and the potential to attract a wide range of participants and opportunities through the Second International Conference for Arctic Research Planning (ICARPII) 2005-2006 and the International Polar Year (IPY) 2007-2008.

The recent developments in Canada allow the PACE initiative to begin in 2005 on the two main polynyas of the Canadian Arctic: the North Water and the Cape Bathurst Polynya. In the North Water, the contemporary physical, biological and biogeochemical signals are as strong and unambiguous as can be expected in a complex natural system: work there will extend an established database of three years duration. Work in the Cape Bathurst Polynya will provide important contrasting information, since that region shows a high degree of interannual variability in its ice cover relative to the North Water. Canadian scientists have stepped forward to lead the international effort with a combination of funded projects that will bring a dedicated research icebreaker to the region annually over the next 14 years (the *Amundsen*, funded by the Canada Foundation for Innovation or CFI). PACE work can be seen to begin with CASES and extend into a time-series effort with a newly funded Canadian program called ArcticNet. Although ArcticNet includes multiple projects or themes, its "Theme 1" is explicitly designed for ocean-based research in the North Water and Cape Bathurst Polynya, following the guidelines of PACE. (For further information about CASES, the *Amundsen* or ArcticNet, contact Louis Fortier, at *Louis.Fortier@bio.ulaval.ca* or visit the CASES website at *www.giroq.ulaval.ca/cases/status.html*). Links with other international efforts are obvious; e.g., the ongoing Arctic Subarctic Ocean Flux Study (ASOF); the developing pan-Arctic Shelf-Basin Exchange program (SBE); and future projects under consideration by ICARPII and IPY steering groups. Ultimately, in promoting long-term study of polynyas during this time of overt environmental change in the Arctic, the IAPP is encouraging the public and the scientific community together to consider and recognize what these archetypal ecosystems of the Arctic have to teach us about our changing Earth and its resources.

The concept of polynyas as archetypal Arctic ecosystems

In calling polynya ecosystems archetypal for the Arctic, we are recognizing their importance in recent Earth history, as recorded in the sedimentary and other natural records, in written history, and in the earliest orally transmitted records. Recognized over millenia by native hunters and their communities and in recent centuries by foreign explorers, two key features make a polynya unique: the seasonal absence of ice and an abundance of marine birds and mammals. The physical occurrence of open water and the biological support of higher trophic levels reflect the endmember issues for PACE. What changes can we expect in the physical-chemical forcing functions that lead to a seasonally recurrent polynya? How will those changes influence the ability of the ecosystem to support the highest trophic levels, including humans?

We consider the North Water, known as the "Gateway to Greenland," as an excellent example of an archetypal Arctic ecosystem: it should always hold a central place in PACE. Within the last 4500 years, its marine production has provided resources for at least four Inuit immigration waves from the Canadian Arctic to Greenland. Recent excavations on the Greenland side of Smith Sound (Arneborg and Gulløv, 1996) have revealed that the Dorset culture, despite their lack of any boats or kayaks, survived until around the year 1300 by utilizing seal, walrus and seabird populations available from land and fast ice. Modern day Greenlanders derive from immigrants of the Thule culture from the 12th century, who were able to navigate the North Water to harvest whales and to quickly colonize the rest of the hospitable areas of West Greenland. During this entire period of human existence in the area, the North Water has provided necessary living resources for native inhabitants, in particular sea birds. Seabird feather remnants in ^{14}C-dated peat deposits at the Carey Islands (Brassard and Blake, 1978) indicate that seabirds were present in the North Water between 6500 and 4500 years ago. Today, the polynya is home to roughly two-thirds of the world population of the Dovekie *Alle alle* and more than half of Greenland's population of the Thick-billed Murres *Uria lomvia*. The seabirds migrate seasonally to West Greenland and Newfoundland, where they are essential quarry of local hunters during winter. The northernmost permanent human settlement in the polynya region, on the Greenland side of the North Water, is the Qaanaaq Municipality. By 1999 (Anon, 2000), Qaanaaq was populated by 857 people (only 56 born outside of Greenland), the majority of whom for their subsistence rely upon small-scale fishing and hunting for Narwhal, Polar Bear and seals, the top predators of the polynya ecosystem.

Critical multi-level cooperation

Development of shared goals and steadfast cooperation among nations and their citizens, indigenous peoples and scientists, is essential for successful long-term research in the Arctic. PACE demands it. No single country or segment of society offers all of the required expertise and facilities to engage in decadal-scale research of coupled physical-biological systems. Every scientific discipline can benefit from native knowledge, just as progress in scientific understanding of complex systems can benefit local and distant decision-makers. The NEW and NOW projects established a solid foundation for interaction between the cultures of different scientific disciplines. During NOW, similar groundwork was laid for direct cross-cultural exchange between scientists and local Arctic communities, which were visited by the icebreakers while fully engaged in the project. CASES builds further on this exchange process with advance visits to local communities and direct involvement of native Arctic hunters in the ice camps and overwintering-ship aspects of the expedition. Through a new program called Schools on Board, high-school students have worked with scientists shipboard for first-hand experience with the scientific process and Arctic research. What happens in polynyas as archetypal ecosystems, and how they may change in future, holds special (if not vital) interest to indigenous peoples and broad interest to the public. For the scientific community, obtaining quality-controlled measurements over many years simultaneously with the evolution of empirical and model-based experiments as new ideas and understanding emerge is not a trivial goal. It is an imperative one, however, in the face of a changing environment, the effects of which ripple through society at all levels. Whether a specific measure of environmental change is linked to the outputs of industrial society or to natural Earth cycles, to local (internal) or distant (external) forcings, all signs indicate that research in the Arctic in the foreseeable future will be conducted in environments undergoing change. Fundamental to IAPP research is the need to understand how and when a changing physical-chemical environment will translate into an altered ecosystem.

Guiding principles

A long-term research plan of the temporal and conceptual scale envisioned requires a set of guiding principles or objectives that can be revisited regularly as the program evolves in the face of inevitable contingency. For PACE, the IAPP-SCG has identified the following overall goals:

- *engage in focused multidisciplinary and international efforts, following the successful models of NEW, NOW, and ongoing CASES.*

The successes of NEW and NOW depended strongly on effective leadership, regular networking through international workshops, and adequate facilities. PACE begins in the North Water and Cape Bathurst Polynya as a result of experienced Canadian leadership, facile at international collaboration and cross-cultural exchange, and acquisition of the research-dedicated icebreaker *Amundsen* and significant new research funding (ArcticNet). The combined resources of several nations, however, will be needed to supplement the efforts of the *Amundsen* (as well as other Canadian Coast Guard icebreakers) expected to visit the region annually in summertime for the next 15 years. More intensive or special-project work could be facilitated as icebreakers from other nations join this first Canadian contribution to PACE. Supply flights to the Thule Air Force Base (TAB, local name "Pituffik"), operated by the US Air Force, and Short Take-Off and Landing (STOL) flights at the new local airstrip in Qaanaaq could provide year-round land-based access to the region. Highly skilled dog-sled and dinghy operators could provide assistance to ice-camp activities, as they have for decades; indeed, these local hunters can become essential partners in long-term time-series research and monitoring efforts conducted via ice camps. Recent experience on the *Amundsen* during the overwintering phase of CASES has fully demonstrated the value, scientifically and culturally, of native wildlife observers working side-by-side with scientists from the ship itself. Meteorological objectives can be supported by the unmanned weather station, operated by the Danish Meteorological Institute, at Carey Islands situated in the middle of the North Water. The basic weather data collected there every three hours by this automatic satellite-linked station are transmitted to the WMO forecast system and available to researchers. Additional collective facilities and resources can be envisioned for each of the Arctic polynyas targeted for parallel study.

- *develop predictions from observation-based models, capitalizing on existing and developing databases.*

The IAPP-SCG recognizes that the application, and further development where needed, of various classes of disciplinary and coupled models in advance of more data collection is the ideal mode of proceeding. We also identify, however, the need for ongoing measurements in the North Water in particular, so that the existing three-year NOW data sets can comprise the beginning of the long-term database required to make and to test predictions. There is a need to move forward to avoid any serious temporal gap in this database. The possibility that thresholds for key parameters will be crossed, and changes to the ecosystem begun, before models can be applied effectively or before the first long-term elements of PACE (e.g., Theme 1 of the Canadian program ArcticNet) can be launched, should not be overlooked. As a practical matter, therefore, models will be applied and tested in parallel with continued data collection. Fortunately, some types of models and the relevant expertise are already available for application to the North Water (and the Cape Bathurst Polynya, as its data base grows).

For example, pelagic ecosystem models have been designed for high-latitude environments, including polynyas (Touratier et al., 2000), and the prediction of key organisms and significant carbon fluxes as a function of altered parameters. Physical models that simulate the opening and closing of a polynya as a function of wind stress and air temperature are also available (Darby et al., 1994) and evolving in sophistication (Biggs and Willmott, 2001; Morales Maqueda et al., 2004). Large-scale coupled ocean-atmosphere models have been developed to explore the Arctic response to increasing greenhouse gases (Meehl and Washington, 1990), although many issues remain to be resolved, especially in terms of the strength of both positive and negative feedback mechanisms (Randall et al., 1998). Development of a polynya-specific class of high-resolution, 3-D, coupled physical-chemical-biological models is in order (Yager et al., 1995; Yager, 1996); prototypes from the Barents and Greenland Seas exist (Slagstad and Wassmann, 1997; Slagstad et al., 1999). Sufficient data are available from the North Water to begin to meet this objective.

- *consider both internal and external forcing functions in evaluating polynya-specific responses*

An environmental change with the potential to influence the structure and functioning of a polynya ecosystem may occur locally (an internal forcing) or at a distance (an external forcing). Paying attention to both categories of influence is a cornerstone of PACE, one that helps to identify and prioritize essential measurements to be made over a long-term time-series effort (see below). The definition of forcing functions, however, cannot be left at the binary level of internal versus external. The lines are blurred by disciplinary perspectives, as well as by inherent links and feedbacks between local and distant phenomena and responses to them. A forcing function may come in the form of a physical departure from the norm (e.g., local cloud cooling [Key et al., 2001], limiting primary production) or a chemical shift in nutrient ratios (insufficient silica to support a five-month diatom bloom; Tremblay et al., 2002a). It may also come in the form of a biological shift in primary producers or dominant predators (e.g., migrating seabirds leaving before depletion of zooplankton stocks, enabling emergence of an alternative predator). Moreover, the same large-scale external forcing (e.g., switch in the Arctic oscillation or vector of ice movement in the Arctic Ocean) may effect one polynya location differently from another (Barber and Hanesiak, 2003), precluding simplistic extrapolations from local-scale to large-scale or vice versa.

The ideal plan will thus involve parallel time-series assessments of key features of multiple polynyas on a pan-Arctic basis. Given the recent funding or Canadian proposals (CASES, CFI and ArcticNet) and anticipated international contributions, at least a cross-comparison between two polynyas, the Cape Bathurst Polynya and the North Water, will be achievable in the coming decade under the auspices of PACE. Plans for parallel work in European waters (the Storfjorden Polynya off Svalbard) and on the Russian Shelf (Laptev and Kara Sea polynyas) are also beginning and may benefit from developments related to ICARPII and the International Polar Year 2007–2008.

Cross-comparative study of the Cape Bathurst Polynya and the North Water will represent a solid beginning to PACE. Each polynya is located at a pivotal, though very different, point in relation to the thickened coastal ice of the Canadian Archipelago and to Arctic Ocean fluxes (see mooring locations along the Greenland-Canada-Alaska shelf break for the ASOF program). The Cape Bathurst Polynya is situated to the west within the general circulation pattern of the Arctic Ocean, while the North Water lies to the east at an Arctic outflow point. Although the nearby Mackenzie River shelf system is well studied geologically and hydrodynamically (Carmack and Macdonald, 2002; Macdonald et al., 1998, 1999, 2002), the Cape Bathurst Polynya itself is still known mainly by its archetypal features – the presence of open water and of marine mammals and birds. The timing and areal extent of this polynya are highly variable annually, as revealed by satellite imagery of the ice pack; recent modeling work indicates strong negative anomalies in the ice cover (more open water) in recent years (Barber and Hanesiak, 2003). The higher trophic levels are indeed present in the Cape Bathurst Polynya, but understudied, and in relatively low numbers in the case of marine birds. The biological underpinnings of this polynya ecosystem and the extent of carbon export from it, however, are only poorly known. Some recent opportunistic work in the polynya in 2000 suggests that the summer phytoplankton bloom, at least in that ice-heavy year, was short-lived and of limited magnitude (Wells and Deming, 2002). The ongoing CASES project (see preliminary results at the CASES website noted earlier) will improve understanding of the coupled physical-biological basis and extent of the whole polynya system dramatically, and thus improve the ability to predict outcomes of future scenarios. Already, the overwintering legs of CASES have yielded surprises, including converging data sets on phytoplankton and ice-algal biomass that indicate that the onset of detectable growth in this year (2004) began soon after the sun appeared above the horizon in February. The ultimate magnitude of this year's primary production in the region remains to be seen.

In sharp contrast, the North Water has been a reliably recurrent and high-production ecosystem for recorded history, as recently confirmed on the century scale by the marine sedimentary record (Hamel et al., 2002). The main players (from viruses to whales) and processes (from atmospheric exchange to sediment burial) governing the current functioning of this ecosystem are known (Deming et al., 2002). The internal factors accounting for the temporal and spatial disposition of the polynya are unambiguous: e.g., the timing and force of the wind arriving from the west and the formidable ice bridge that straddles Kane Basin during the open-water season. Examination of two decades of satellite imagery suggests that the physical system is poised for change, given the evidence that features of the ice bridge have been weaker in recent years (Barber et al., 2001). If an external change in Arctic Ocean circulation also occurs (Johnson et al., 1999), then the chemical make-up of the source waters to the polynya may well shift. Tremblay et al. (2002a) argue that the nitrate to silicate ratio is delicately poised now. A shift away from silica in the source waters may reduce the extent and magnitude of the diatom bloom in the North Water, which in turn will affect the higher trophic levels.

- *assess interannual, decadal and longer (paleo) variability in key physical, chemical, biological parameters.*

An evaluation of variability in key features of polynyas on the interannual scale for the next decade is the primary objective of the PACE plan, as specifically reflected in the first of the funded Canadian-led elements (Theme 1 of ArcticNet). The Canadian Foundation for Innovation has provided funding for a research-dedicated Canadian Coast Guard icebreaker (and associated equipment) with a lifetime of about 14 years, thus enabling the logistics for an extended observational program in the Canadian Arctic and beyond (via international charters). The icebreaker, recently inaugurated the CCG *Amundsen* (August 2003), is stationed in Quebec City. Ship plans include an annual late-summer tour of northern Baffin Bay (the North Water) through the Northwest Passage to the Cape Bathurst Polynya and back. Because evaluating variability at higher temporal resolution may have important ecosystem ramifications, seasonal aspects of time-series work were considered when developing the list of core parameters to measure annually (see below). Collective experience from NOW (see special issues edited by Barber et al., 2001; Deming et al., 2002) suggests that remotely collected measurements (e.g., by satellite, from meteorological stations, by long-term moorings) could be used to assess the opening of the polynya and start of the bloom season in springtime. Ice camps, especially on the Greenland side, should be particularly helpful in this regard. Shipboard work (e.g., mooring service, CTD casts, biological sampling) would be conducted towards the end of the bloom season, when the ecosystem is heterotrophically mature, including maximal carbon export to depth (Hargrave et al., 2002), in the west along Ellesmere Island and the region is most accessible by sea.

Changes over the annual-decadal time scale are of prime interest to human populations in the Arctic, but being able to place such relatively short-term perspectives into longer-term context is very important. The IAPP-SCG considers that the PACE plan should include paleooceanographic elements that do not necessarily require annual visits to the study sites, but can instead rely upon one-time expeditions to recover core materials required for a centurial-to-millenial analysis of variability in polynya functions. The few available studies of the Arctic sedimentary record at depths equivalent to our targeted sites already demonstrate the promise of this approach. For example, the western Arctic appears to have seen greater climate variability (warming) during the Holocene period (as recently as a few thousand years ago) than what has been measured over the last century (Darby et al., 2001).

- *evaluate links between key parameters in relation to emergent properties of the polynya ecosystem, especially the support of higher trophic levels.*

We consider that the overriding uncertainty in predicting significant changes in the properties of a polynya ecosystem lies in the identification of key physical, chemical, and biological parameters and their possible threshold values, beyond which the existing balance between trophic levels will shift. In developing a decadal database of such parameters, we may learn that ecosystem change is rapid, as implied by a consideration of threshold values (and by recent developments in the Bering Sea ecosystem; Hunt et al., 2002), or gradual, requiring years to reach a "sea change." Either way, the selection of the core parameters, and a set of them that is logistically feasible to obtain on an annual basis, is the critical first step. The SCG has thus spent much of its recent meeting time deliberating the minimum set of parameters that would constitute a long-term time-series program capable of yielding the desired information. In addition, we used the forum of the International Polynya Symposium, held in Quebec City 9–13 September 2001 (extended in duration by world events), as a unique opportunity to engage the larger international community in the discussion. The following set of parameters emerged as critical to measure and evaluate over time. The parameters are stated in simple form, without ascribing specific methods, since the list is intended as a basis for further deliberation and refinement. Some elaboration is provided in Appendix II. Note that important, if not critical, information that can be obtained via modeling efforts, analysis of satellite imagery, or paleooceanographic studies (as discussed earlier) is not included explicitly below.

Core parameters

Physical parameters

1. Radiative forcing
2. Cloud type, extent and optical depth
3. Wind speed and direction
4. Ice dynamic and thermodynamic states
5. Ocean mixed layer
6. Coupling to oceanic and atmospheric teleconnections

Chemical/biogeochemical/microbial parameters

7. Air-sea exchange of CO_2
8. Macronutrients (nitrate and silicate)
9. Organic pools (dissolved and particulate, microbial processing)
10. Particle fluxes (and microbial alterations)
11. Benthic remineralization

Biological parameters

12. Phytoplankton and primary production
13. Zooplankton population structure and development status
14. Bird feeding responses
15. Marine mammal habitat use
16. Macrobenthos

The measurement of many of the parameters above will easily be accompanied, often or always, by related measurements (e.g., chlorophyll fluorescence and transmissivity with T and S from CTD casts; micronutrients along with nitrate and silicate, etc.). Our goal has been to identify the main characterization needed to identify significant change to the ecosystem and its forcing functions. The ***general hypothesis*** underlying our ecosystem deliberations is that an increase in new production translates into a greater abundance of higher trophic levels: specifically, indications of an upward shift in macrozooplankton should be evident. Two macronutrients – nitrate and silicate – are essential to analyze in this context, since they support the (currently) dominant diatom blooms responsible for the majority of new production and carbon flux to the seafloor. Although pelagic–benthic coupling is typically tight in polynyas (patterns in benthos from both the NEW and NOW reflected patterns in new production and carbon flux), benthic remineralization and macrobenthic analyses are needed to help recognize a comparative loosening of the coupling, if and when that happens.

Macrozooplankton are identified as essential organisms to evaluate, due to their central role as prey items for the higher trophic levels, from fish to birds to marine mammals. Changes in bird feeding strategies (surface versus diving), somewhat more tractable than changes in fish or marine mammal behavior, are expected to be direct indicators of changes in the availability of suitable prey. New remote tracking techniques for marine mammals, however, should also be well-suited to a long-term time-series study. Changes in the shape of carbon-flux profiles are expected to indicate shifts from a high-new-production/macrozooplankton system to a low-new-production/microheterotrophic system. In the latter scenario, the shift in balance from large prey items to smaller prey items (and a greater role for microorganisms in general) is expected to signify an impending reduction in higher trophic levels.

Concurrent with ecosystem evaluations by these measurements would come information on carbon sequestration at depth, an important consideration in climate change studies and the possible role of polynyas as carbon sinks in the overall Arctic (and global) equation. Coherent results from the many approaches to measuring the output of the biological pump have eluded researchers in the temperate ocean for decades (Ducklow et al., 2001). Yet, in both the North Water and the Northeast Water, carbon flux measurements are remarkably coherent (Cochran et al., 1995; Yager et al., 1995; Deming et al., 2002), suggesting that polynyas may be ideal locations from a global perspective for evaluating and predicting the transport of particulate carbon (and other elements) to depth. Because the fate of elements in flux, whether particulate or dissolved, is a function of microbial activity, the timing is also right to bring to bear on these longstanding and critical issues the power of the burgeoning genomics and proteomics movements (NRC Committee, 2003). Ultimately, measurements of the various physical parameters outlined here will allow deduction of forcing factors responsible for changes to the ecosystem and fluxes from it. The research community will then be positioned to assess links and feedbacks to larger-scale factors and events, in the Arctic and globally, over the decadal time frame of analysis.

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Appendix II: Elaboration of Core Parameters by SCG Members and Others

Physical parameters: David Barber, John Hanesiak, David Holland, Peter Minnett, Andrew Willmott

We require better information on the climate state variables (both oceanic and atmospheric) that drive polynya processes. These state variables need to be measured over a range of temporal scales, which we know from previous research span the hour to inter-annual scale. We suggest two sampling strategies, integrated together within a framework such as could be supported through ArcticNet or PACE. The first involves intensive "process studies," selected to coincide with a particular season of a polynya (e.g., fall, winter, or spring); the second involves "time-series studies" whereby measurements would be automated and/or conducted remotely. These studies should be conducted in a highly coupled and scientifically integrated environment; for example, using coordinated sampling from the CCG *Amundsen*, moorings, atmospheric profiling, surface energy balance stations, and remote sensing. The following temporal and spatial sampling schemes are suggested.

Inter-annual sampling should consider at least a 10-year period. We base this on growing evidence for a periodicity in the synoptic scale processes which drive sea-ice dynamic and thermodynamic processes (e.g., Maslanik et al., 1996; Polyakov et al., 2000, 2003; Polyakov and Johnson, 2001; Drobot and Maslanik, 2003; Dumas et al., 2003; Holland, 2003; Karcher et al., 2003; Zhang et al., 2003). For example, a variety of authors have shown that the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO) and the Northern Annular Mode (NAM) are highly interrelated and appear to have multilevel periodicities spanning the 7- to 10-year scale (Proshutinsky and Johnson, 1997). Although speculative scientifically, this periodicity has the added benefit of providing us with a sufficient time series to evaluate change and variability at scales important to policy and management decisions associated with adaptation to Arctic climate variability and change.

Spatially, we require high-resolution measurements within the "process studies" periodically throughout the "time-series studies." These process studies are required within representative seasons of polynya evolution (e.g., closing, stability and opening; Barber et al., 2001). Measurements are required through the full range of spatial scales from meter to hundreds of kilometers. Emphasis however will be on calibration/validation of processes that can be measured through the time series studies in the ocean, sea ice, and atmosphere. Calibration and validation of remote sensing will enhance our ability to scale up and across the various temporal and spatial domains required by PACE.

We require "process studies" systematically throughout a 10-year time frame to further refine the physics of processes operating across the ocean-sea ice-atmosphere (OSA) interface and to understand the linkages coupling these physical processes to biogeochemical cycling within the polynyas. Between the in situ "process studies," we require time-series information for selected variables. Previous work on polynyas indicates that the pertinent variables can be estimated from the scientific importance of each to physical-biological coupling in the polynyas, as well as the technological capability to measure these variables reliably within the OSA system (Ingram et al., 2002). Finally, we propose that the state variables to be measured should contribute to the remote-sensing retrievals of these variables over large spatial and temporal scales, thus supporting the "time-series studies" framework. We suggest the following:

1. Radiative forcing

Partitioning of solar radiation into reflection, transmission and absorption is a well-known and important state variable for physical and biological processes operating within polynyas. Unfortunately, the measurement of albedo as a climate state variable over the full range of temporal and spatial scales required is still an elusive scientific goal (Hanesiak et al., 2001). Longwave fluxes are equally important in the overall radiation balance of polynyas; they must be measured over the same temporal and spatial scales as the shortwave fluxes (Minnett, 1999; Hanafin, et al., 2001; Intrieri et al., 2001). We propose to install both integrated and spectral measurements for irradiance, radiance and emission of both shortwave and longwave radiation with the OSA. These measurements need to include the euphotic zone in the ocean, the ocean/sea-ice interface, and the sea-ice surface and volume. Albedo measurements are also required at the top of the atmosphere. Radiative exchanges across the OSA will thus be estimated from the results of moorings, surface met stations, in situ measurements, and remote sensing.

2. Cloud type, extent and optical depth

Clouds, which dominate the exchange of mass and energy across the OSA interface, remain a significant unknown in numerical process models within polynyas (Curry et al., 1993, 1996), especially when one considers the surface radiation balance of polynyas (Minnett, 1995). Because of the early reduction in ice concentration, the role of clouds is even more pronounced than over other arctic marine areas. The top height, optical depth, percent cover, layering and base temperature of clouds are identified as significant variables which can be measured during both "process studies" and "time-series studies" (Minnett, 1999). In situ observations will be made following established practice using instruments such as an all-sky camera, ceilometer, moisture-profiling radiometers and Fourier-domain interferometers. Satellite remote sensing systems will be used both with existing time-series datasets (e.g., AVHRR) and new and improved sensors (e.g., CERES, MODIS, MISR, CloudSat, etc) for retrieval of cloud type, extent, thickness, and optical depth. New and existing algorithms such as CASPR (Key, 2002), BDAS and TOVS (Francis, 1994) retrievals will be applied.

3. Wind speed and direction

Wind speed and direction are particularly important to surface forcing of polynya processes (Pease, 1987; Morales Maqueda and Willmott, 2000). They provide coupling between the deeper portions of the ocean, the surface layer and the atmosphere. Sea-ice dynamics are driven to a large extent by atmospheric forcing, such that feedbacks between dynamic and thermodynamic processes in sea ice become very important. Model estimates of wind climate states are a well-known limitation in the North Water and may also be a problem with smaller polynyas, such as the circumpolar flaw lead polynyas. ECMWF and NCEP fields are simply not suitable for estimation of most of the processes that are required to understand fully the physical-biological relationships in polynyas. We therefore propose to install wind direction and speed onto our surface met stations and to continue with development of remote sensing estimates of surface winds. The latter can be accomplished either through direct observation of surface roughness (scatterometer- and radiometer-based approaches) or through indirect measurement of surface pressure fields (SEB stations and met stations) and estimation of surface winds through analysis of these fields.

4. Ice dynamic and thermodynamic states

Ice motion (dynamics) and growth and decay (thermodynamics) are essential elements of polynya processes (Wilson et al., 2001). Direct measurement sensors can be installed during field programs to measure ice velocity and keel depth (upward-looking sonar). Ice-thickness beacons can be used to follow the thermodynamic growth of ice and telemeter the data through Argos to labs in the south. Snow thickness can be measured in situ using well established sonar profiling techniques and inversion of the brine/temperature relationships evident at the base of first-year sea ice using microwave remote sensing. Surface roughness measurements can be used to estimate thickness (through use of airborne and spaceborne scatterometer measurements, laser profiling and EM induction techniques). The development of the estimation of the onset of melt over sea ice (water in liquid phase in the snow) through to the formation of melt ponds on sea ice (using active and passive microwave remote sensing; Barber et al., 1999) should be continued. These suites of measurements can provide much-improved estimates of the mass balance of sea ice in polynyas and the rates of change in both the dynamic and thermodynamic sea-ice processes. Of direct relevance will be a better understanding of the processes that give rise to ice-bridge formation and how bridges function in the opening, maintenance and closing of polynyas.

5. Ocean mixed layer

How the atmosphere and sea-ice components of the OSA are coupled to the upper ocean (mixed layer) throughout the seasonal cycle represents a significant element of the physical-biological coupling and, indeed, of the formation, maintenance and closing of polynyas (Ingram et al., 2002; Uttal et al., 2002). In the fall, surface cooling can lead to penetrative convection that brings deeper, warmer waters up into the mixed layer where they retard ice growth. In the winter, the circulation pattern and the ongoing thermodynamic growth of sea ice directly controls the formation of intermediate and bottom waters in the Arctic basin and surrounding seas. In the spring, sea-ice melt produces a freshwater pulse that stabilizes the mixed layer and thus enhances primary and secondary production. The processes that drive the coupling across the OSA can be measured using ocean moorings and *in situ* measurements with CTD profiling instruments. Work to develop remote sensing estimates of ocean convection and melt water stability of the mixed layer should also be continued. The influence of freshwater fluxes on mixed layer processes must also be a focus of field investigations. Time-series measurements of freshwater fluxes can be obtained through gauged watersheds and remote sensing of plume dynamics.

6. Coupling to oceanic and atmospheric teleconnections

The processes described above are all driven, to varying extents, by the oceanic and atmospheric setting within which a polynya is embedded. The synoptic context sets the stage for the climate states and the rates at which they will change in both space and time. Oceanic processes are important with regard to deep water formation, intrusion of warmer water masses to the base of the sea ice and the overall exchange of freshwater between the Pacific, Arctic and Atlantic oceans (Aagaard and Carmack, 1989). Similarly, large scale atmospheric circulation drives the patterns of divergence and convergence in large scale sea-ice dynamics (aka., the central arctic pack ice), thereby establishing the conditions that allow many types of polynyas to occur. For example, both the North Water and the Cape Bathurst Polynya rely to different extents on the distribution of the central arctic pack ice. Climate-reporting stations surrounding the northern hemisphere can be used to estimate state variables at this synoptic scale. Modeled data from ECMWF and NCEP can also be applied to estimate synoptic fields of significance in OSA coupling (e.g., 500-hPa heights, air temperatures, wind states, precipitation, etc). Indices from the AO, NAO and NAM can be used as indicators of hemispheric trends in atmospheric teleconnections, but we will continue to treat processes at the OSA as events, driven at smaller and shorter time scales, than are captured in general indicators such as these. The use of oceanographic CTD profiling (WOCE and others), tracer experiments, ASOF measurements and existing mooring locations to keep abreast of the changes in the ocean basins as they impact the OSA interface and polynya dynamics should be investigated.

Chemical/biogeochemical/microbial parameters

7. Air-sea exchange of CO_2 (Leif Anderson, Lisa Miller, Tim Papakyriakou)

The high latitude oceans that are covered by sea ice have been considered less important to the air-sea exchange of CO_2 than the oceans that are not capped by ice. This situation does not pertain to polynyas, since they are open much of the year. During summer, when biological production peaks, the partial pressure of CO_2 (pCO_2) in the surface water will be low and a flux from the atmosphere is sustained. In fact, this flux has been suggested to rectify, since the water that takes up the CO_2 will flow under the ice before organic matter is remineralized in the fall/winter, causing the pCO_2 to increase to super-saturation (Yager et al., 1995). The evolution of pCO_2 during the summer season is best followed by one (or several) buoys that register sea surface temperature (SST), pCO_2 in the surface water and in the overlying atmosphere, as well as the wind speed. These buoys should be complemented with standard oceanic station work, measuring hydrography and the carbonate system, preferable early and late in the productive season. This will make it possible to elucidate the changes in the carbon inventory of the water column.

During winter, polynyas become sea-ice production factories, forming large quantities of high salinity brine while the sea ice is typically blown away. This overall process has been suggested to be very efficient in taking up CO_2 from the atmosphere (Anderson et al., 2003). When sea ice is formed from surface water that is under-saturated with respect to CO_2, there will be a continuous flux from the atmosphere to the surface water. The CO_2 taken up will go into the brine, which due to its density will sink to deeper layers, thus keeping the surface water at the same "low pCO_2". This process is very efficient in mixing the very top surface layer and is thus independent of wind speed, the key variable for gas exchange in open water. The wind is nevertheless an important factor in keeping the polynya open. The effect of this uptake of atmospheric CO_2 is best studied in early spring, by collecting water samples from the surface down to the very bottom and analyzing for nutrients, oxygen and the carbonate system.

The basic concept that sea ice acts as a lid on the air-sea exchange of CO_2 is currently being reconsidered by CASES researchers (Miller et al., 2004). Carbon dioxide transfer, especially through young and thin sea ice, must still be considered an open question, requiring rigorous investigation under varying ice, wind, and temperature conditions. Although significant technical developments are still required, long-term (annual) deployment of both marine and atmospheric sensors on moorings or drifting ice buoys should be an effective way to study controls on gas fluxes through sea ice. With the methodologies currently available, this type of work can be carried out effectively from ships, whether frozen in during winter (e.g., the *Amundsen* for CASES) or in motion during the marginal seasons of spring and late fall.

8. Macronutrients (Jean-Eric Tremblay)

Long-term inter-annual variability in nutrient supply

Arctic polynyas are located in areas where the surface circulation is highly dynamic, either through gyres, transpolar currents, or river discharge. The source waters that feed these physical features contain strikingly different inventories and ratios of the three major nutrients nitrate, silicate and phosphate (e.g., Jones et al. 1998; Tremblay et al., 2002a). Source waters that originate in the Bering Sea typically contain high amounts of the three nutrients, whereas those from the Atlantic Ocean are enriched in nitrate relative to silicate and phosphate. Rivers typically supply very high amounts of silicate, but relatively low amounts of nitrate and phosphate (e.g., Gordeev et al., 1996).

The first two major polynyas targeted by the Canadian contribution to PACE (through ArcticNet) are located in the Canadian Archipelago, where roughly one third of the total Arctic outflow exits through narrow channels (Aagard and Coachman, 1974). Due to their position at the head of two of these channels, the North Water and the Cape Bathurst Polynya receive large volumes of Arctic waters that underwent little biological depletion during transit beneath the polar ice cap. The latter polynya also receives variable amounts of fresh water depending on the discharge of the Mackenzie River. Recent IAPP work (NOW and CASES) in these polynyas predicts that their nutrient load will be highly susceptible to changes in river discharge, the configuration of the general Arctic circulation, and the erosion of the upper halocline during regional mixing processes (Tremblay et al., 2002a). The current consensus is that these changes are driven by climatic oscillations and possibly climate warming (Walsh et al., 1996; Morison et al., 1998). Vertically-resolved measurements of nitrate, silicate and phosphate (using automated colorimetric methods, Grashoff, 1999) will be critical to assess inter-annual variability in the supply of plant nutrients during PACE.

<u>Nutrients as time-integrative signals of biological activity</u>

The residual inventory of nutrients in surface waters in late summer provides a time-integrative estimate of new production during the productive season. This estimate is possible because the difference in nutrient inventory between the upper mixed layer and the deeper layers reflects biological consumption, which can be converted into new carbon production. New production is a particularly useful quantity that represents the amount of carbon potentially exportable to higher trophic levels, renewable resources and the deep ocean. In addition, the ratio of the different nutrients in the residual, late-summer surface pool provides an indication of the taxonomic composition of the primary producers responsible for the nutrient drawdown. For instance, a large depletion of nitrate and a mild depletion of silicate indicates that diatoms did not contribute much to overall productivity (see section 2 below). Complete utilization of nitrate seems to be the norm in Arctic polynyas (Tremblay et al., 2002b; Kattner and Budéus, 1997; Smith et al., 1997), indicating that new production is expected to be proportional to nitrate supply via the large-scale circulation (see above). For this reason, and because they open early and are often positioned "strategically" upstream of the main escape routes of Arctic waters (e.g. Fram Strait and Nares Strait), polynyas behave like traps that strip nutrients from surface waters at the onset of their southward transit. A variable fraction of the organic matter thus produced subsequently settles, effectively removing nutrients from surface waters (Michel et al., 2002). These processes are hypothesized to exert a strong negative effect on the productivity of downstream regions, possibly as far south as the eastern North American seaboard (e.g. Wallace et al., 1995).

The build-up of regenerated forms of nitrogen in late summer, especially ammonium and dissolved organic nitrogen (DON), is indicative of an active recycling community where bacteria and other heterotrophs degrade the organic matter synthesized during the productive period. For instance, an increase in the concentration of regenerated nitrogen within the upper mixed layer in late summer indicates that a sizeable portion of the nitrogen consumed during the bloom was effectively retained in surface waters. The vertical distribution of regenerated nitrogen in the upper part of the water column may thus indicate the extent to which surface waters act as retention or export systems. Similarly, the concentration and vertical distribution of nutrients in deep waters are related to subsurface microbial activity, benthic recycling and, for ammonium and nitrite, denitrification in superficial sediments (Devol et al., 1997). These processes are quantitatively important in the nutrient budget of polynyas and the Arctic Ocean in general. Along with those mentioned above, vertically-resolved measurements of ammonium, nitrite (automated colorimetric methods) and DON (persulfate oxydation; Sharp et al., 2002) will complete the picture.

9. Organic pools (and microbial alterations; see also 10 and 12) (Jody Deming)

The amount of carbon pooled as dissolved organic carbon (DOC) in the global ocean roughly matches the amount of carbon in our atmosphere; even small changes to the oceanic DOC pool can be expected to perturb the global carbon cycle significantly (Hansell and Carlson, 2001; Hedges, 2002; Amon, 2004). The Arctic Ocean differs from all other oceans in many obvious ways, but particularly in the higher concentrations of DOC held within it (Amon and Benner, 2003). Although the sources and fate of this large pool of carbon are poorly known in general, the disproportionate riverine input (relative to other oceans) of terrestrial DOC is understood to explain the high values in large part (Amon, 2004). For the DOC pool to remain high, however, the primary consumers of DOC – the microbial, and especially bacterial, communities – must be operating in limited fashion relative to temperate-ocean communities. Explanations for limited DOC consumption in the Arctic include the recalcitrant nature of the terrestrial fraction of the carbon and potentially high DOC thresholds for microbial activity at subzero temperatures (Amon, 2004; Pomeroy and Wiebe, 2001). Field results, however, suggest that bacterial communities respire carbon at rates that should reduce the DOC pool significantly (Rich et al., 1997; Yager and Deming, 1999; Middelboe et al., 2002). The imbalance in DOC budgets between production and consumption terms calls for more study of the problem in general (Amon, 2004).

From the perspective of changing ecosystem structure in polynyas, anticipated shifts in balance from large prey items to smaller prey items – and thus a greater role for microorganisms in general – also logically translates to greater consumption of DOC, especially the more labile fraction of it. As the DOC budget is altered microbially, so will the efficiency of carbon transfer to larger organisms and higher trophic levels be affected (reduced). Changes in microbial communities, their performance in carbon cycling and their effects on the ecosystem at large can be recognized by late-summer field work after primary production gives way to a predominantly heterotrophic system. Key measurements to make include pelagic bacterial abundance, production and respiration, along with bacterial alterations of POC to DOC (see 10). Use of molecular and genomic techniques to deduce the main players and genes they are expressing in the course of cycling both carbon and nitrogen (see 8) would provide a mechanistic understanding of conventional budgetary assessments of stocks and rates, as well as the resident genetic potential for change.

10. Particle fluxes (and microbial alterations) (Paul Wassmann, Jody Deming, Kirk Cochran)

Vertical export of biogenic matter from the euphotic zone, through the aphotic zone and to the seafloor is essential to understanding the pelagic-benthic coupling that pays a crucial role in carbon flux studies. In most of the Arctic, pelagic-benthic coupling is poorly resolved. Measurements derive primarily from the adjacent margins characterized by seasonal loss of ice cover (Wassmann et al., 2003) and from polynya studies (e.g., Amiel et al., 2002; Hargrave et al., 2002). ^{234}Th-derived POC fluxes, on the whole, are consistent with sediment trap observations, provided that the POC/^{234}Th ratio and procedures used to estimate the ^{234}Th flux are evaluated carefully enough (Moran et al., 2003). The vertical export depends on the stratification and vertical mixing features of the water column, new production, phytoplankton key species, suspended biogenic matter and the entire suite of biomass and nutrient-regenerating processes of the heterotrophic community. So far, the role of large-sized phytoplankton and larger zooplankton (faecal pellets) has been recognized, but in-depth studies indicate that pico- and nanoplankton, many of them probably heterotrophs, dominate the vertical export and that coprophagy is an important process in many Arctic shelf seas. With regenerative processes strongly regulating the vertical export (Olli et al., 2002) and an efficient microbial food web and aggregate formation/destruction system involved (Middleboe et al., 2002; Huston and Deming, 2002), current concepts of pelagic-benthic coupling, derived from coastal regions or traps exposed in the oceanic interior, do not appear valid for the arctic shelf seas and ice-covered regions. A stringent connection between plankton and vertical export investigations is required to understand the regulation of vertical flux in the "twilight" zone. The deeper regions of the Arctic Ocean are characterized by high retention of vertical carbon export in the twilight zone, but marginal ice zones can also show this tendency. Over-wintering of large, long-lived zooplankton such as copepods (often advected from the North Atlantic) and appendicularians appear to play an important role in the attenuation of vertical flux (Wassmann et al., 2003). In the decades to come, the dramatic northwards retreat of the marginal ice zone due to global warming will result in an extensive, stratified area of open water that stretches from the shelves far into the Arctic Ocean. As a consequence, primary production and vertical export of biogenic matter will increase in the peripheral zone and, by analogy, in the expanding and likely new polynyas of the contemporary permanent ice cover. In contrast, the low productivity, high retention and low biogenic export region, which at present dominates the central Arctic Ocean basin, will shrink.

11. Benthic remineralization (Søren Rysgaard)

The input of organic matter to the sediment surface is often characterized by a strong pulse following the spring and summer blooms in the water column (Atkinson and Wacasey, 1987; Hebbeln and Wefer, 1991). Several studies have documented high standing stocks of benthic fauna in Arctic regions (Grebmeier et al., 1988; Ambrose and Renaud, 1995; Piepenburg and Schmid, 1996). An efficient transfer of organic matter produced in the water column to the sea floor through a close pelagic-benthic coupling, together with low metabolism of benthic fauna, are among the reasons why high benthic biomass can be maintained. Despite permanently low temperatures, near-shore Arctic benthic communities mineralize organic matter as efficiently and as rapidly as communities at lower latitudes (Rysgaard et al., 1998; Glud et al., 1998). Mineralization in the sediment will greatly affect the porewater concentrations of solutes such as oxygen. Measuring the oxygen penetration depth within the sediment with microsensors (Revsbech et al., 1983) offers a fast and reliable way to gain information about the benthic mineralization and the distribution of the activity. If these measurements are combined with flux measurements of oxygen and dissolved inorganic carbon in intact sediment cores, they will deliver information about the relative importance of benthic animals to total organic degradation, i.e. the sum of microbial and animal degradation (Rasmussen and Jørgansen, 1992).

Biological parameters

12. Phytoplankton and primary production (Jean-Eric Tremblay)

Central issues concerning phytoplankton processes in Arctic polynyas are the taxonomic composition, timing and magnitude of primary production. IAPP investigations in the North Water and the Northeast Water indicated strong differences in these three characteristics (Smith et al., 1997; Tremblay et al., 2002b), but there is not enough information to assess whether these differences are polynya-specific or result from inter-annual variability in physico-chemical forcing and climate variability. The factors that control the three characteristics of primary production must be investigated, as they may largely determine the pathways of carbon flow and the success and production of higher trophic levels in polynyas.

One of the enigmas of the Arctic Ocean is why diatoms (e.g. *Chaetoceros socialis*), prymnesiophytes (e.g. *Phaeocystis pouchetii*) and other taxa achieve varying degrees of success in different regions and at different times. This question is central because different algal groups have different implications for carbon fluxes. Diatoms are thought to favor the production of the herbivores that are essential for the transfer of carbon toward the upper trophic levels (Legendre and Le Fèvre, 1989), whereas *Phaeocystis* colonies are not grazed unless very large herbivores are present (Hamm et al., 2001). Hence diatoms generally enhance the biological pump (i.e., the vertical flux of carbon from the atmosphere to the deep ocean), whereas *Phaeocystis* colonies and small flagellates alike tend to remain in surface waters where microbial activity can release carbon back into the atmosphere. *Phaeocystis* are typically successful in the Greenland and Barents Seas (Smith et al., 1991), but there are yet no indications that they reach high biomass levels in polynyas of the Canadian Archipelago. Reasons for these differences are poorly understood, with very little information on inter-annual variability.

Explanations for the success of different taxonomic groups potentially reside in different requirements and physiological adaptations for nutrients and light. Diatoms have an absolute requirement for silicic acid and appear to be poorer competitors than *Phaeocystis* for phosphorus (Hegarty and Villareal, 1998). These traits are likely to put diatoms at a disadvantage in Atlantic-derived waters with relatively low silicate and high N:P ratios. The relative contribution of the Bering Sea, the North Atlantic and rivers to the waters that flow through polynyas (see above) may thus influence the success of different taxonomic groups. In addition, there is increasing evidence that *Phaeocystis* photosynthesizes more efficiently and grows faster than diatoms under low irradiance (e.g., Van Hilst and Smith, 2002). This adaptation implies that *Phaeocystis* should dominate systematically under the low light environments characteristics of polynyas in late winter and late summer, but this was not the case in the North Water during 1998 and 1999 (Lovejoy et al., 2002). Clearly, the timing and taxonomic composition of primary production are influenced by more than one environmental forcing, possibly an interaction between the surface circulation (nutrient ratios, seeding effect) and the factors that set the light climate (e.g., incident solar radiation, albedo, ice cover and type, mixed layer dynamics).

During PACE, phytoplankton investigations need to be coordinated with nutrient determinations. The residual pool of nutrients in surface waters allows an estimation of the magnitude of blooms and carries the taxonomic signature (nutrient ratios) of primary producers (see above). Direct measurements of phytoplankton characteristics should include vertically-resolved chlorophyll *a*, particulates (carbon, nitrogen, phosphorus and biogenic silica), and taxonomic composition (microscopy). Flow cytometry and HPLC can be especially useful to identify and quantify key pigment markers for *Phaeocystis*, diatoms and other taxa. Rate measurements should include photosynthetic characteristics (PAM fluorometry and P-E curves in photosynthetrons), primary production and nitrogen assimilation (simulated *in situ* incubations).

13. Zooplankton population structure and development status (Louis Fortier, Hans-Jürgen Hirche)

In Arctic waters, the annual pattern in the population dynamics of several zooplankton species is strongly pulsed, with reproduction, growth and accumulation of reserve compressed during the short interval of biological productivity in summer and early fall (Hirche and Kwasniewski, 1997; Madsen et al., 2001). The population structure and condition of dominant zooplankton species in early fall represent excellent integrator state variables of the summer transfer of primary production to the upper trophic levels (Ringuette et al., 2002). The individual daily growth history of first-year juvenile fish is recorded in its otolith (e.g., Meekan and Fortier, 1999). Plans are in place (through the Canadian element of PACE, ArcticNet) to assess the population structure (stage composition), lipid condition and reproductive status of three copepod species (*Calanus glacialis, Calanus hyperboreus, Metridia longa*), as well as the early growth of Arctic cod (a key species in the Arctic food web), in September of each year during the annual expedition to refurbish moorings in the North Water and the Cape Bathurst Polynya. Relating copepod population dynamics and Arctic cod early growth measured in the fall to summer sea-surface temperature and phytoplankton production as monitored by RADARSAT and SeaWifs orbiters will enable an evaluation of the impact of climate variability on the food web at annual and decadal scales.

14. Seabird feeding responses (Knud Falk)

For higher trophic levels, seabird populations offer a range of parameters sensitive to the temporal and spatial variation in the marine environment (Mehlum et al., 1996; Springer et al., 1996; Suryan and Irons, 2001); at lower trophic levels, the birds act as "natural sampling devices." Colonial breeders are most feasible to use as indicators, since they allow a reasonable sample size – whether studied at sea or in the colonies. If PACE ship-based research priorities are mainly aiming at end-of-season polynya conditions, seabird parameters will require sampling at colonies; hence the priority below:

<u>Species considerations:</u>

By including diving as well as surface-feeding predators in the sampling plan, an optimal spread in life strategies and dependency on the marine environment is achieved. Due to their circumpolar distribution, the species Thick-billed Murre (a deep-diving fish and macro-zooplankton predator, foraging on pelagic and benthic prey to more than 100-m depth) and the Black-legged Kittiwake (a surface-feeding [max 1-m depth] fish and zooplankton predator) would be available as study objects in most polynyas. They have already proved highly different indicators to variable marine conditions. In some polynyas other species may be optimal study objects; in the North Water the Dovekie is a key component in carbon turnover (Karnovsky and Hunt 2002) and should be included.

Parameters:

Breeding phenology. The timing of breeding is highly dependent on spring foraging conditions and one of the most sensitive indicators of annual and long-term shifts in foraging conditions. This parameter is also one of the simplest to collect in open-nesting species (not Dovekie).
Breeding success. This parameter reflects resource access in the vicinity of the colonies in high and late summer. In multi-egg species (kittiwakes) the response has a higher resolution (0-3 eggs and chick) than in single-egg species (murres, Dovekie). Breeding success can be studied relatively easily once study plots have been defined.
Adult and chick diet. The adults select optimal food items for chick meals, which can be studied/sampled upon return (non-destructive) or at the feeding grounds (shooting from boat). Inter-annual and long-term variations reflect shifts in availability of suitable prey. Indirect methods integrate trophic position over longer time spans (blood [non-destructive]: weeks, muscle: months); stable isotope (C and N) analysis of adult blood samples would be a feasible sampling method that can be applied in most colonial species with relative ease (Hobson et al., 2002). In addition, for Dovekies, fatty acids markers could be applied in assessing shifts in the composition of their copepod diet and main prey (Falk-Petersen et al., 2000).
Foraging activity and distribution. At-sea distribution reflects main foraging areas, but requires aerial of ship surveys over large areas. If regular ship operations become part of PACE, standard transects could be mapped repeatedly (also in late summer). Foraging effort differs with local oceanographic conditions and prey access (Falk et al. 2002) and should be monitored at a number of standard sites in the chick-rearing period; however, it is often time-consuming and should not be carried out annually.

15. Marine mammal habitat use (Sue Moore)

Marine mammals integrate and reflect Arctic ecosystem variability from the top down. To forage efficiently, they must find areas of dense prey concentrations and thereby identify "hotspots" of secondary production. In addition, whales and seals are important components of the Inuit diet and hold a special position in Native culture. An analysis of beluga and bowhead whale distribution in the Alaskan Arctic demonstrated that each species selects habitat based upon bathymetric features likely associated with prey availability and that, in bowheads, habitat selection varies with ice cover (Moore, 2000). Results of satellite tagging studies have demonstrated basin-scale movements for beluga tagged in the Canadian Arctic (Richard et al., 2001) and at Point Lay, Alaska (Suydam et al., 2001), two genetically-distinct populations. Of note, tissue samples from the Point Lay whales, which feed in the Canadian Basin, carried heavier OC burdens than belugas sampled in Cook Inlet, Alaska (Becker et al., 2000).

To incorporate marine mammal sampling into PACE, three types of data are needed: seasonal occurrence for a suite of species (cetaceans and seals) within and outside the polynyas, individual movements within and outside the polynyas and tissue samples. Thus, three "integrator state variables" or sampling techniques are required: passive acoustic detection and tracking via an array of autonomous recorders; satellite tagging of at least two, possibly three, species selected for variation in diet (e.g. bowheads, belugas, and ringed or bearded seals); and capability to obtain tissue (and possibly gut content) samples from marine mammals, either via association with Native hunters, biopsy darting, or (preferably) both. Taking these measurements on marine mammals in concert with physical, chemical and trophic measurements will provide an integrated suite of data that captures ecosystem variability from both ‘bottom up’ and ‘top-down’ perspectives. The unprecedented nature of this proposal is highlighted by the cetacean tagging results of Heide-Jorgensen et al. (2002), who conducted studies in Baffin Bay in near-time, but not integrated with the NOW polynya study. Pan-Arctic coordination of such efforts under PACE will define a critical step forward in the study of marine mammals and habitat use.

16. Macrobenthos (see also 11 above) (Jody Deming)

In productive Arctic shelf regions and especially in polynyas, the presence of high standing stocks of benthic fauna (Grebmeier et al., 1988; Ambrose and Renaud, 1995; Grebmeier and Cooper, 1995; Piepenburg and Schmid, 1996) and their rates of oxygen consumption (e.g., Rowe et al., 1997; Grant et al., 2002) are linked to overlying production. Interpreting the balance between magnitude of stocks, which reflect long-term growth, and rates, typically measured in short-term incubations, is often a complex issue (see also 11), but close pelagic-benthic coupling in the Arctic does have a strong seasonal component. Importantly, that component can include shifts in the dominant fauna contributing to carbon cycling, from micro-meiobenthos to macrobenthos, as the productive season progresses (Grant et al., 2002). Persistent climate-induced changes in the timing and magnitude of overlying production are expected to alter both species composition and standing stocks of Arctic benthos (Klages et al., 2004). Much can be learned from long-term, annual, seasonally consistent measurements of benthic parameters in polynyas throughout the Arctic, as envisioned by PACE. Assessments of constancy or change in the dominant species or size class at the end of the bloom season over many years would provide important indicators of persistent changes in environmental conditions. Where higher trophic levels are dependent on benthos for nutrition, changes in seafloor communities will be critical to overall ecosystem sustainability. Additional measurements of size-partitioned rates of benthic oxygen consumption will add to the evaluation of ecosystem health as linked to environmental change.

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