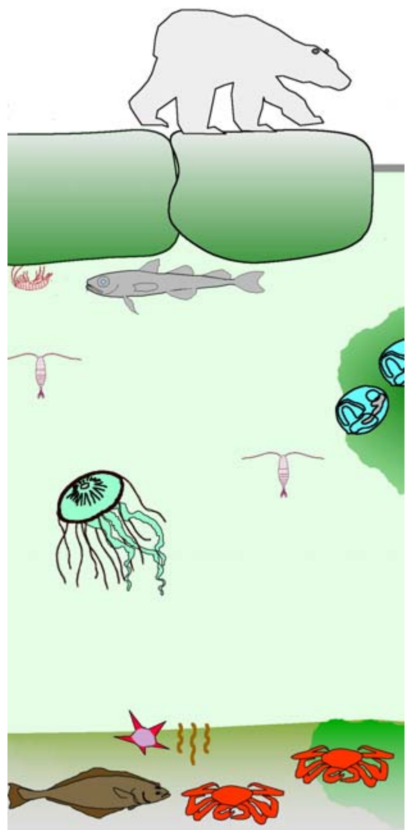
Arctic Census of Marine Life (ArcCoML)



PROGRAM PROPOSAL
(15 April 2004)

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1. Executive Summary

The Arctic Ocean is unique on Earth in its physical and biological properties. It is the most extreme ocean in regard to the seasonality of light and its year-round existing ice cover. It is also the ocean, where changes related to climate change might be strongest expressed. The tremendous on-going changes make the effort to identify the diversity of life in the major three realms (sea ice, water column and sea floor) an urgent issue. Current knowledge indicates that the Arctic seas hold a multitude of unique life forms adapted to the extremes. This proposal aims at documenting the present Arctic biodiversity using an international Pan-Arctic view. This program will consolidate what is known and fill remaining gaps in our knowledge, to a large extent through dedicated efforts in the International Polar Year 2007/2008.

2. The study area

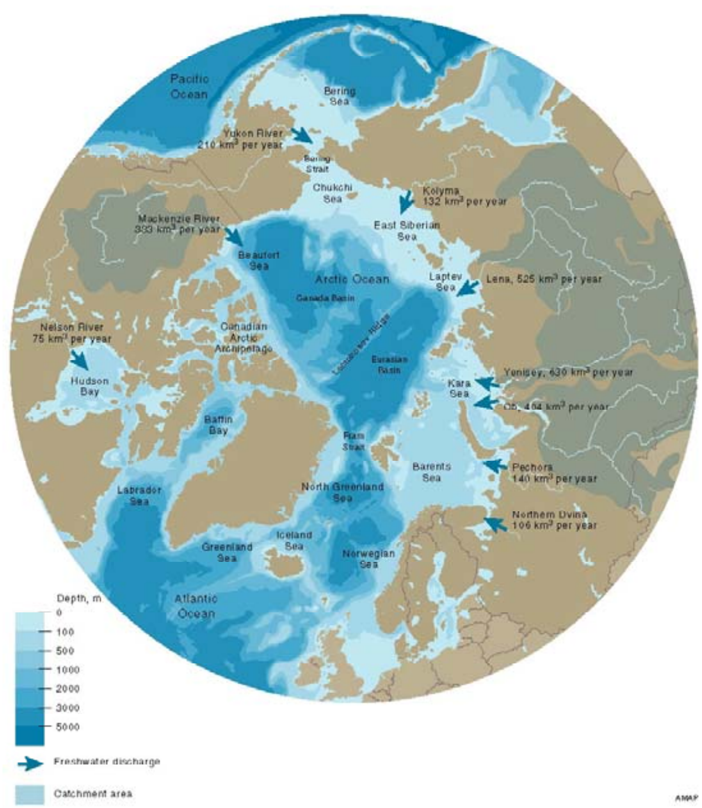

Fig. 1: Map of the Arctic (Source: Arctic Monitoring and Assessment Program)

The Arctic Ocean is a mediterranean sea (total area: about 10^7 km^2), which covers the region between Bering Strait on the Pacific and Fram Strait on the Atlantic side (Carmack 1990; Fig. 1). Continental shelves represent ~50% of the Arctic Ocean: the Barents, Kara, Laptev, East Siberian and Chukchi shelves are shallow and broad (600-800km) while the shelves from Alaska to Greenland are narrow. The Arctic deep-sea is divided into the Canadian or Amerasian Basin (max. depth 3800m) and the Eurasian Basin (max. depth 4200m), divided by the Lomonossov Ridge (sill depth 1400m). Both basins are further subdivided: the Canada and Makarov Basins, divided by the Alpha-Mandeleyev Ridge, form the Amerasian Basin, and the Nansen and

Amundsen Basins, divided by the Nansen-Gakkel Ridge, from the Eurasian Basin.

The major exchange of water between the Arctic Ocean and the world's oceans is through Fram Strait (sill depth 2600m; Carmack 1990). On the Pacific side, Bering Strait today provides only a shallow (50 m depth) connection to the North Pacific, which has been intermittently closed by glaciation during the last 1-2 million years; the Pacific deep-water connection closed 80-100 million years ago. The water column is composed of three main layers, a low-density surface layer, an intermediate layer which receives warm and salty water from the Atlantic, and a deep dense layer formed through convection (Aagard et al. 1985). The surface waters carry Atlantic waters as well as Polar Water, which are diluted with fresher water, and Arctic Surface Water. The deep water experiences very slow exchange and, in the Canada Basin, has a residence time of ~450-500 years (Macdonald et al. 1993).

The Arctic receives tremendous freshwater inflow from both rivers and sea ice meltwater. Most of the riverine inflow comes from the Russian rivers Yenisei, Ob, and Lena and the Canadian MacKenzie River, which together contribute ~2000 km^3 yr^{-1} (Treshnikov 1985). The salinity gradients derived from these freshwater sources in the river deltas and beyond structure the biological communities in the areas of their influence (Deubel et al. 2003).

Sea ice covers ~$7x10^6$ km^2 in the summer and twice that in the winter (Walsh & Johnson 1979) with a decreasing trend in recent years (see below). Multi-year sea ice of 2-3m thickness covers about 50% of the Arctic Ocean, and nearly all of the central deep basins. Maximum thickness of >10m are reached in areas of extensive ridging. Sea ice formed on the Siberian shelves takes some 2-4 years to migrate across the Transpolar Drift, while sea ice transported in the Beaufort Gyre remains in the Arctic Ocean for ~5-10 years before its release into the North Atlantic (Eicken 2003, Haas 2003). The sea ice is both critical in the heat exchange budget of the Arctic Ocean, as well as a habitat for life ranging from viruses to polar bears and subsistence hunters (Horner 1985, Gradinger 2002, Krupnik & Jolly 2002).

3. Arctic Census of Marine Life Initiative (ArcCoML)

3.1 Arctic Census or Marine Life: Significance and urgency

The observed and predicted changes in global climate are estimated to have the earliest and most pronounced effects in high latitudes (Manabe & Stouffer 1994). Recent investigations have estimated a decadal loss in Arctic sea ice of 2-3% (Parkinson et al. 1999) and a reduction in sea ice thickness of an average of 1m in the Chukchi and Beaufort Seas (Rothrock et al. 1999). Measurable temperature shifts have been recorded for the Arctic shelf shallow water bodies, the transition zones from sub-Arctic to high Arctic conditions (Hunt & Stabeno 2002). The dramatic magnitude of these ongoing changes underscores the pressing urgency for obtaining baseline information on the composition, diversity and functioning of Arctic marine biological systems.

The effects of Arctic climate change are expected to be most pronounced on the shelves with their tight cryo-pelagic-benthic coupling (Grebmeier & Barry 1991, Feder et al. 1994, Grebmeier et al. 1995), but will extend into the deep Arctic Ocean that receives a considerable portion of its carbon from the shelves (Aagaard et al. 1981, Schauer et al. 2002) and from sea ice algal production (Gosselin et al. 1997). Changes in hydrographic conditions (e.g. warming of sea surface temperature, changes of the mixed layer, and reduction in sea ice extent), will have dramatic effects on the timing and spatial distribution of ice-associated and pelagic primary production, and subsequently on the deposition of carbon to the benthos. Changes in carbon supply to the benthos in turn will have cascading effects into higher trophic levels, such as marine mammals and sea birds, and, hence, impact the functioning and biocomplexity of the entire system (Moore 2003).

There are a number of examples where consequences of recent climatic regime shifts, have already been expressed in biological systems of high latitudes (Francis et al. 1998, Benson & Trites 2002). These changes not only relate to timing of blooms and magnitude of biogeochemical fluxes, but also affect biodiversity and species composition. During the recent climate-caused regime shift in the Bering Sea, for example, unusual coccolithophorid blooms occurred (Iida et al. 2002) and may replace the previously occurring summer flagellate community (Schuhmacher et al. 2003). Another example is the substantial increase in gelatinous zooplankton in the Bering Sea that is discussed in the light of climate change (Brodeur et al. 1999). These and other examples from the North Pacific suggest that regime shifts may affect species inhabiting different realms in different ways, or affect similar species in the same realm in opposite directions (Benson & Trites 2002).

Like any biota, the polar flora and fauna is highly adapted in their life history, ecology and physiology to the extreme and highly seasonal conditions of their environment (Thiel et al. 1996, Clarke 1998, Pörtner & Playle 1998). Changes in the environmental conditions will have direct effects on the marine biota on multiple scales, from communities and populations to individuals

(Schumacher et al. in press). These effects can only be detected through long-term monitoring of key species, communities and processes (e.g. SEARCH Science Plan 2003). For monitoring and assessment of changes, the availability of baseline data is crucial. Currently, several large-scale process-oriented investigations, e.g. the "Shelf-Basin-Interactions Studies" (SBI http://sbi.utk.edu, USA), the "Canadian Arctic Shelf Exchange Study" (CASES http://www.cases.quebec-ocean.ulaval.ca/index.html, Canada) and the "Carbon flux and ecosystem feedback in the northern Bering Sea in an era of climate change" project (CABANERA, Norway) investigate some of the Arctic's continental shelf and slope environments, their connectivities, and their response to change. The focus of these and other ongoing studies in the Arctic is on processes, which is also the focal point of the major agencies funding Arctic work in this decade (e.g. NSF, NSERC, European Commission, etc.). While processes are immensely important, it has been documented repeatedly that they are critically impacted by the composition of biota involved in them. Consequently, species level information is essential to discussions climate change, its expressions and effects. The different functioning of the three Arctic biotic realms, sea ice, water column and benthos, plus the fish communities exploiting them, makes each particularly useful at addressing complementing climate change-related impacts on biodiversity.

3.2 The known

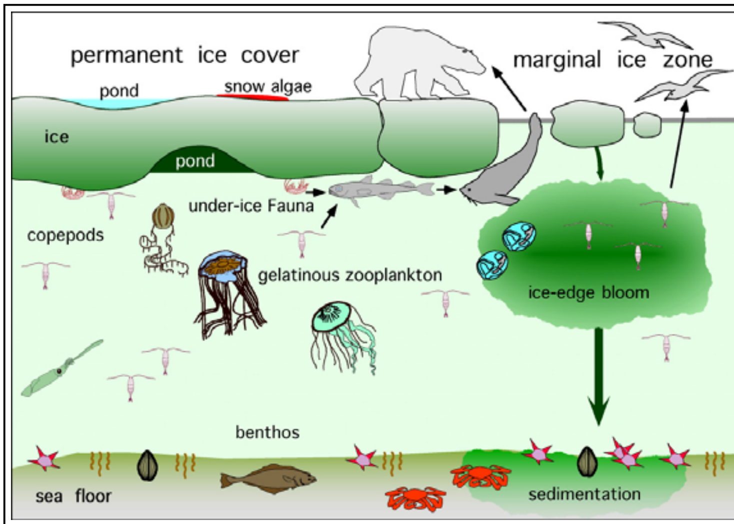

Fig. 2: Schematic representation of the Arctic marine ecosystem and its interactions. Comprehensive taxonomic representatives and all interactions have not been included.

3.2.1 Sea ice - The known

The Arctic sea ice and its related biota are unique, and its year-round existence allowed the development of ice endemic species. The specialized, sympagic (=ice-associated) community within the sea ice is found in the liquid filled network of pores and brine channels (Weissenberger et al. 1992; Eicken 2003) or at the ice-water interface (Horner 1985, Gradinger, 2002). Until recently, diatoms were considered the most important primary producers inside the ice in terms of abundance and productivity (Medlin & Priddle 1990, v. Quillfeld et al. 2003), but a greater complexity is now appreciated (Gradinger 2002, Lizotte, 2003): Flagellated protists also contribute substantially to the structure and dynamics of the ice biota community (Thomsen & Ikävalko, 1991, Ikävalko & Gradinger 1997). Ice algal activity accounts for ~50% of total primary productivity in the ice-covered Arctic (Gosselin et al. 1997) and is tightly linked with the other Arctic marine realms through sedimentation and life cycles (e.g. Grebmeier & McRoy 1989, Peinert et al. 2001, Michel et al. 2002, Leventer 2003). Protozoan and metazoan ice meiofauna, in particular turbellarians, nematodes, crustaceans and rotifers, can be abundant in all ice types. (Carey 1992, Gradinger et al. 1991, 1999, Gradinger 2002, Michel et al. 2002), while larvae and juveniles of benthic animals (e.g. polychaetes and mollusks) migrate seasonally into the ice matrix to feed on the ice algae in shallow waters (Gradinger 2002, Schnack-Schiel 2003, Gradinger et al. subm). Our knowledge on the species composition of ice meiofaunal communities is yet limited to few studies (e.g. Agatha et al. 1993, Friedrich 1997).

A partially endemic fauna, comprising mainly gammaridean amphipods, thrive on the epibionts at the underside of ice floes (e.g., Hop et al. 2000, Werner & Gradinger 2002, Gradinger & Bluhm, in press). Locally and seasonally occurring at several 100 individuals m^{-2}, they are important mediators for particulate organic matter from the sea ice to the water column through the release of faecal pellets (e.g. Werner 2000, Michel et al. 2002). Ice and pelagic crustaceans are the major food sources for Arctic cod (*Boreogadus saida*) that occurs in close association with sea ice (e.g. Andriashev et al. 1980, Gradinger & Bluhm, in press) and acts as the major link from the ice-related food web to seals and whales (e.g. Bradstreet & Cross, 1982).

While previous studies of coastal and offshore sea ice provided a glimpse of the seasonal and regional abundances of the sympagic biota, biodiversity in these communities is virtually unknown for all groups, from bacteria to metazoans. Many taxa are likely still undiscovered due to the methodological problems in analyzing ice samples (e.g. Ikävalko & Gradinger 1997, Gradinger 1999a,b, Gradinger et al. subm.). Recent studies have revealed tremendous regional gradients in abundances and activities of ice related biota (e.g. Gradinger 2002), making a Pan-Arctic approach essential to fully appreciate the diversity within this habitat. The study of diversity of ice related environments if urgently required before they ultimately change with altering ice regimes and the likely loss of the multi-year ice cover (e.g. Gordon & O'Farrell 1997, Serreze et al. 2003).

3.2.2. Pelagic - The known

The growth season of phytoplankton is severely constrained in Arctic Seas by snow and ice cover, low light angles and a relatively short season. The classic view is that phytoplankton production begins in April and ends in early September with a growth curve characterized by a single peak in primary production (PP) in late June to early July (Cushing, 1959). Enhanced biological activity in the pelagic zone occurs on the Arctic shelf areas, where the seasonal retreat of the sea ice allows for the formation of ice-edge algal blooms (Smith, 1990). The melting of sea ice stimulates algal growth as more light enters the sea and the reduction of surface increases vertical stability. Phytoplankton blooms in spring are mainly dominated by diatoms and *Phaeocystis pouchetii* (e.g. Gradinger & Baumann 1991). The tremendous gradients in the large Arctic estuarine systems cause defined phytoplankton species assemblages, dominated by freshwater, brackish water or full marine taxa (e.g. Nöthig et al. 2003).

Zooplankton research in Arctic waters can be traced back nearly a century, with the earliest records restricted primarily to the coastal waters (Lappo et al. 2003). Waters of the continental shelves have now been studied in variable taxonomic detail in the Barents, Kara, Laptev and Chukchi/Beaufort Seas (review by Smith & Schnack-Schiel 1990), while the East Siberian Sea, and Canadian Archipelago (Conover & Huntley 1991) through northern Greenland have been particularly understudied. Due to their high abundance and ease of capture, the taxonomic composition (Brodsky 1983, Sirenko 2001) and life history of the larger more common copepods in the Arctic Ocean is relatively well understood (Smith & Schnack-Schiel 1990). The same cannot be said for the smallest copepod species that are variably missed by collection techniques (Hopcroft et al. *subm.*), deep-water taxa (e.g. Kosobokova & Hirche 2000, Auel & Hagen 2002), or the more fragile gelatinous forms (Raskoff et al. *subm.*).

Historically, effort has concentrated on copepods of the genus *Calanus* because they appear to dominate zooplankton biomass (e.g. Smith & Schnack-Schiel 1990, Mumm et al. 1998, Thibault et al. 1999, Ashjian et al. 2003). As in most oceans, smaller copepod taxa are actually numerically dominant (e.g. Conover & Huntley 1991, Kosobokova & Hirche 2000, Auel & Hagen 2002), yet relatively few studies (Kosobokova 1980, Pautzke 1979, Ashjian et al. 2003) have used sufficiently fine meshes to fully assess their contribution. Although copepods typically predominate in the basins, there is a broad assemblage of other holoplanktonic groups in the Arctic (e.g. Sirenko 2001) that are only occasionally reported in full detail (e.g. Mumm 1991, Richter 1994, Kosobokova & Hirche 2000). These non-copepod groups in particular hold the greatest promise for discovery of new species and trophic importance because they have been largely ignored or biased against by collection techniques.

Larvaceans (=Appendicularians), for example, have been shown to be abundant in Arctic polynyas (Ashjian et al. 1995, Acuña et al. 1999) and common in the central Arctic (Kosobokova & Hirche 2000, Auel & Hagen 2002). Similarly, important and common predatory groups, such as the chaetognaths, amphipods, ctenophores and cnidarians have received detailed report in only a few surveys (Kosobokova & Hirche 2000, Auel & Hagen 2002). Arctic chaetognaths may represent considerable biomass (*ibid*), and are thought to be important in controlling *Calanus* populations (Falkenhaug & Sakshaug 1991). Hyperiid amphipods can also be common in Arctic waters (Mumm 1993, Auel & Werner 2003), and a similar potential to graze a notable proportion of the *Calanus* population (Auel & Werner 2003). The importance of ctenophores and cnidarians in surface and deep waters, and their grazing impacts, are also particularly under-appreciated (Stepanjants 1989, Swanberg & Båmstedt 1991, Siferd & Conover 1992, Raskoff *et al. subm.*). The basic biodiversity of all these gelatinous animals is grossly underestimated in polar waters (Pagès 1997, Pesant *et al*. 1998). Based on submersible experience in other oceans, we expect to discover at least twice as many species in most groups as currently described.

3.2.3. Benthos - the known

Benthic communities in general depend on food supplied from the water column. In high latitudes, the amount of sedimenting food particles rather than temperature *per se* is restraining growth and survival of benthic organisms (Clarke 1983). On the Arctic shelves, particle transport from the pelagic realm to the benthos is relatively large over the ice-free period, and the benthos, therefore, plays a greater role in system production and turnover than at lower latitudes (Høpner-Petersen & Curtis 1980, Grebmeier & Barry 1991). As a consequence, substantial benthic biomass in some areas (Grebmeier et al. 1995) can support major feedings grounds of resident and migrating mammals and sea birds (Gould et al. 1982, Highsmith & Coyle 1992). Enhanced primary production at frontal systems, polynyas and along the ice edge significantly enhances benthic biomass and structures benthic community composition (Grebmeier & Cooper 1995, Schewe & Soltwedel 2003).

To date, the Arctic shelf macro- and megafauna have received most attention while meiofauna and microbial communities are less well studied. Crustaceans (in particular amphipods), polychaetes and bivalve mollusks dominante the macrofauna (Grebmeier et al. 1989, Highsmith & Coyle 1990, Sirenko 1998, Feder et al. 1994a, Deubel 2000). Infaunal benthic community composition is mainly determined by grain size of sediments and the productivity of the overlying water masses (Grebmeier & Barry 1991). The epibenthic megafauna is, at most sites studied, dominated by ophiuroids with up to several 100 individuals m^{-2} (Piepenburg et al. 1996, 1997, Starmans et al. 1999, Sejr et al. 2000). Other conspicuous epibenthic faunal elements include, e.g., sea urchins in the Barents Sea (Bluhm et al. 1998) and sea cucumbers and epifaunal bivalves in the Laptev Sea (Piepenburg & Schmid 1997).

In contrast to the shelves, the Arctic deep-sea has received very little attention. Early studies on slope and deep-sea benthos, mostly conducted from the Arctic drifting stations (Mohr & Geiger 1968, George & Paul 1970, Paul & Menzies 1974), as well as more recent work in the Amerasian and Eurasian Basins (Kroencke 1994, 1998, Clough et al. 1997, Deubel 2000, Bluhm et al. *subm.*) reported low infaunal abundances and biomass and a dominance of deposit feeding groups (Deubel 2000, Iken et al., subm.). Comparison with temperate deep-sea region densities shows overlap with the lower values reported from across the North Atlantic deep-sea (compiled by Levin and Gooday 2003). At the levels of phylum, class and order, the soft-bottom deep-sea fauna is similar to that of shallower water soft bottom habitats (Gage 1978). This seems to also be the case in the Arctic: polychaetes, crustaceans, and bivalves dominated the few deep-sea samples while less frequent taxa comprised sponges, cnidarians, tunicates, ophiuroids and various worms. At present, ~350-400 benthic macro- and megafauna species have been listed for the deep waters of the central Arctic Ocean adjacent to the Eurasian Arctic (Sirenko 2001). These, like the shallow water species, represent four biogeographic affinities (cosmopolitan boreo-arctic, Atlantic- and Pacific-boreal arctic and arctic endemic species), the distribution of which gives evidence about the geological history of the Arctic (Bilyard & Carey 1980, Golikov & Scarlato 1990, Dunton 1992).

3.2.4 Nekton - the known

Many Arctic marine mammals as well as seabirds depend on the production of fishes, suggesting that significant biomass of these prey exists in the Arctic Ocean. Although fish communities of the nearshore and adjacent regions (e.g. Barents, Greenland and Bering Sea shelves) have been intensively studied for fisheries resources, our knowledge of their diversity and abundance on the continental slope and in the deep basins, particularly of the western Arctic Ocean, is poor. We know from previous research (Stein et al. 2004) that shrimps are common in the deep Arctic; cephalopods are known from the Arctic around Greenland and Russia and also probably occur in the Canadian Basin although none have yet been recorded.

About 66 species of marine or anadromous fishes are known from the eastern Chukchi Sea (Barber et al. 1995), about 65 from the western (N.V. Chernova, *pers. com.*), versus 110 from the (shallow) northern Bering Sea (ibid.). This is a typical northern shallow continental shelf, with low diversity but relatively high fish biomass (Frost & Lowry, 1984). In the more northern, deeper continental slope and abyssal basins, we expect lower biomass and possibly higher diversity. Although there is little regional data on occurrence of fishes at those depths, available data and analysis of video records (Stein et al., *subm.*) shows that there are representatives of at least four families of deep-water fishes present on the mid-slope and deeper: Zoarcidae (eelpouts), Liparidae (snailfishes), Rajidae (skates) and Psychrolutidae (blob sculpins).

3.3 The unknown, the challenges and the unknowable

3.3.1 Is the Arctic impoverished?

In his 'List of species of free-living invertebrates of Eurasian Arctic seas and adjacent deep waters,' Sirenko (2001) listed 4784 species (Tab. 1). This increase of ~1000 species for the same area summarized only seven years earlier (Sirenko & Piepenburg 1994) can be accounted for by recent efforts such as the 10-year Russian-German Laptev Sea study (Kassens et al. 1999). Periods of intense taxonomic study such as this indicate that even on the seasonally accessible Arctic shelves, a marine inventory is not yet complete. The current view, however, still is that species richness on the Arctic shelves is generally lower than in temperate or tropical shelf regions (Gray 2001). Species inventories are likely less complete for the sea-ice due to basin wide under-sampling (as noted previously). Similarly, species inventories in pelagic communities were the largest volumetric domain (i.e. the deep-waters) is under-sampled, also appear lower than most other oceanic regions but have great potential for species discovery.

At present, the biogeography of the Arctic is not equally understood for all realms. Planktonic species, while partly endemic to the Arctic, are believed to be mostly derived from Atlantic origins rather than Pacific (Smith & Schnack-Schiel 1990), despite considerable inflow of Pacific species through Bering Strait. Biogeography is better understood in benthic communities, although experts do not agree on the mechanisms underlying the current species distribution and origins (Nesis 1984, Golikov & Scarlato 1990). Most investigators today do, however, agree on the diverse origin of today's Arctic fauna (Bernard 1979, Golikov & Scarlato 1990, Dunton 1992). The paucity of Pacific origin deep-water species is considered a consequence of the closing of the deep connection to the Pacific 80-100 million years ago, which never re-opened (Zenkevitch 1963, Dunton 1992). The shallow inflow (50m) opening 3-3.5 million years ago allowed and still allows migration of shallow-water and eurybathic Pacific species, but not specific deep-water species, into the Arctic Ocean. The Pacific signature today is, therefore, strongest in the Chukchi shelf fauna, but also notable on the Beaufort, East Siberian and eastern Laptev Sea shelves (Dunton 1992, Sirenko 2001). The opening of the Arctic towards the Atlantic 27 million (Barry 1989) to 40 million years ago (Dunton 1992) happened simultaneously to a cooling phase, which enhanced the development of a cool-temperate Atlantic-character fauna, along with a gradual 'Atlantization' of the Arctic Ocean (Golikov & Scarlato 1990).

Large-scale biodiversity patterns are currently under discussion with regards to bathymetric and latitudinal trends. The deep-sea in particular has recently received attention in this regard because deep-sea areas worldwide have been shown to harbor more species than previously realized (Gray 2002, Brandt & Hilbig, in review). In the more thoroughly sampled North Atlantic, species diversity increases from the shelf to intermediate depths and subsequently decreases in the abyssal plain (Rex et al. 1997). Although Arctic studies to date confirmed the decrease in species numbers with increasing depth (e.g. Anisimova 1989, Fedyakov & Naumov 1989, Deubel 2000), a meaningful analysis capable of detecting potential intermediate maxima or other trends requires more intense sampling to establish basic species inventories. The discovery of at least five new macrofaunal species, and the collection of several species newly recorded for the area, during a small sampling effort in the Canada Basin (Bluhm et al., *subm*.), suggests that a larger number of new species will be revealed with larger sampling efforts.

Similarly, the long discussed trend of a marked latitudinal decline in species richness towards the pole is being reconsidered (Rohde 1998, Rex et al. 2000). Analyses of latitudinal gradients in deep-sea biodiversity suggest this decline towards the high latitudes for certain taxa (Rohde 1998, Rex et al. 2000), but a lack of data from high Arctic regions, especially the deep-sea, presently weakens the generalization of this latitudinal hypothesis. While studies on some taxa, e.g.

Table 1: Number of free-living invertebrate species in various Arctic seas. From: Sirenko 2001

Reference	Number of species	White Sea	Barents Sea	Kara Sea	Laptev Sea	East Siberian	Chukchi
Zenkevitch 1963	N/A	1015	1851	1432	522	N/A	820
Sirenko, Piepenburg 1994	3746	1100	2500	1580	1337	962	946
Sirenko 2001	4784	1817	3245	1671	1472	1011	1168

prosobranch gastropods (Roy et al. 1998), provide convincing evidence in this matter, Dauvin et al. (1996) found no latitudinal gradient in the annelid fauna, the dominant macrofaunal element of soft sediments, between 48 and 90ºN. The lack of comprehensive Arctic deep-sea (and, partially, shelf) sampling makes a generalization of a latitudinal decline for all taxa and both poles premature (Kendall 1996, Clarke & Crame 1997). All contributions towards a species inventory of the Arctic deep-sea help strengthen latitudinal comparisons, because the data are so limited.

3.3.2 The gaps: geographic, taxonomic, and temporal unknowns

Our knowledge of species richness and biodiversity in the Arctic, to some degree, reflects the effort spent on certain taxa and certain regions as well as the techniques used. The Sloan Foundation sponsored the first Arctic Biodiversity workshop held in Fairbanks (April 2003), during which the participants identified geographical, taxonomic and technological gaps. To date, the listed Arctic metazoan invertebrate species are comprised of 60% macrobenthos, 34% meiobenthos and 6% holoplankton (Sirenko 2001). Like in most other oceans, the study of species diversity began with large organisms in easily accessible areas, while smaller, deeper and more elusive forms are very poorly studied, such that the gaps are of varying magnitude for different taxa and regions. For the pelagic system, some groups of zooplankton such as copepods are reasonably well studied, at least in more shallow waters. The importance of some smaller species, however, is underestimated. Very limited information on species richness, diversity and distribution is available for other more delicate groups, such as gelatinous plankton, metazoan meiofauna inhabiting the sea ice, and microbial communities in all three Arctic realms. Particularly the sea ice and planktonic communities are also subject to dramatic seasonal changes and information on these community structures year-round is sorely needed.

For benthic, pelagic and fish communities, most effort has traditionally been invested into the shallow waters of the continental shelves, where sampling is relatively easy during the ice-free summer season. The Barents, Chukchi, Bering, and Laptev shelves have been fairly well studied, while the Eastern Siberian Sea and the fjord systems of the Canadian Archipelago and of Greenland are among the least well known. The shelf breaks and the deep-sea basins of the Arctic Ocean are poorly studied for any taxonomic group, with the deep Canadian Basin being the least known of all. Given the Canadian Basin's long-time separation with little exchange to other deep-sea basins, it will be a particularly interesting area for future study. Benthic, pelagic and sea ice systems are linked to each other and the connectivity between these realms is essential to understanding biodiversity in the Arctic Ocean. Linkages will certainly change from the shelf to the deep seas.

Agreement was reached during the workshop that standardized sampling and processing techniques would help ensure compatibility of data. Image systems associated with towed systems, ROVs and AUVs are appropriate for benthic megafauna and gelatinous plankton, while epibenthic sleds, grabs and cores are reliable quantitative tools for macrofauna, meiofauna and infauna. Shallow coastal areas should be sampled using the already established, standardized NaGISA protocols, while planktonic and deep-sea benthic methods should adopt techniques from other CoML projects were possible (e.g. CeDAMar, MarEco, CMarZ). It was agreed that molecular sequencing should be an integral part of any sampling program. For example, the application of molecular tools with live microscopy will help reveal diversity of bacteria and protists. Standardized ice techniques have to be developed and should include a combination of ice cores and *in situ* techniques such as SCUBA.

Like during many other CoML workshops, it was acknowledged that a considerable wealth of information exists as various disparate databases, records not yet in electronic form, and stockpiles of samples from "process" oriented research that have not been examined in taxonomic detail. The workshop endorsed any strategy that that could help get such invaluable information into an electronically accessible form, ultimately served through OBIS. The Russian Federation was specifically identified as holding a wealth of valuable information needing database support.

3.3.3 Challenges and Unknowables

The challenges of an Arctic Census of Marine Life are manifold, and the most obvious ones are briefly outlined here. The logistical difficulty of sampling in any kind of ice covered waters makes studies of the Arctic, and the deep basins in particular, logistically challenging and limits the number of observations (Spindler 1994, Arrigo 2003). The minimum ice extent in summer allows easier access to the high Arctic for scientific sampling, but the more accessible regions remain those over the shelves; thick multi-year ice remains year-round over much of the basins. Thus, safe access to major parts of the Arctic can only be ensured through the use of an icebreaker. Currently, the nations regularly conducting Arctic research dedicate one to three icebreakers to Arctic research, mostly part-time. Ship-schedules are discussed and planned for on at least 2-5 year horizon (e.g. the German research icebreaker *Polarstern* is already largely committed until the end of 2007). An alternative to more synoptic ice-breaker transits is the use of field stations and ice camps, which allow year-round sampling, but with limited geographic context. Use of ice stations has its own challenges in terms of maintaining logistical support/supplies and the dangers associated with exposure during winter and ice-breakup during late summer.

In addition to the harsh environmental settings, political boundaries, particularly those of Russia, remain a complication to access in some regions. Especially seafloor sampling and imaging can be a ‘hot’ issue in regions valued for their underground resources or those known or suspected for dumping of nuclear and other wastes.

Aside from the logistical challenges, the biggest impediment to understanding Arctic biodiversity is financial, as icebreakers are extremely costly and long cruises are required to cover adequate ground. In addition, most funding agencies these days are interested primarily in funding hypothesis based “process” studies or global change ecosystem studies that target dominant species/groups, and lack a true biodiversity component. In conclusion, it will realistically remain impractical to sample the entire Arctic with complete taxonomic resolution and at a high spatial resolution for the foreseeable future. However, any effort directed specifically toward understanding biodiversity, can make tremendous advances toward improved knowledge of Arctic biodiversity.

4 The Arctic Census of Marine Life initiative: main scientific questions

Based on the provided information, the proposed Arctic CoML aims at the following major goals which are illustrated by more specific examples of the type of question each might address.

1. **Species inventory of the Arctic**
   a. How many species are there on the shelves verses the deep-sea basins in the three realms ice, water column, and benthos, plus their associated fish communities?

b. How does the spatial scale of sampling (area/volume sampled, number of replicates) bias our impression of regional and basin wide diversity?

c. Is the Arctic impoverished relative to lower latitudes in terms of species richness?

d. Are potential trends in species richness (e.g. with depth and latitude), the same in all realms, depths strata and size-classes?

e. Are there any “hot-spots” in species richness / biodiversity?

f. Can we use molecular and chemical tools to assess microbial diversity and community connectivity?

2. Identify bio-geographic affinities and barriers

a. What is the distribution of Atlantic, Pacific, endemic Arctic and cosmopolitan species in the sea ice, water column and benthos?

b. How can the species distribution patterns be linked to the geologic history of the Arctic?

c. How do bio-geographic affinities vary between realms, between shelf verses deep-sea, and as a function of depth in general?

d. How do the major Arctic river runoffs structure biological communities on a pan-Arctic scale?

3. Arctic-boreal cosmopolitans: are they really all one species?

a. Can we distinguish regional differences within one species using traditional (e.g. morphological) tools combined with molecular tools?

4. Relation between species distribution patterns and species richness with environmental data

a. How well do water mass distribution and water mass origins explain species distribution patterns?

b. Is there a match of primary productivity with species richness, abundance, and biomass?

c. What are linkages between biodiversity and ecosystem function?

d. What can we learn about potential climate change impact on biodiversity from correlating species distribution patterns with environmental data?

As the Arctic database develops, these goals and questions will be revised and completed.

Objectives: To address the above scientific questions, the objectives of ArcCoML are to:

1. Implement an ArcCoML structure through a scientific steering group, a network of collaborating researchers and a project office,
2. Identify and accumulate available data,
3. Fully analyze samples that are already available and provide taxonomic training,
4. Fill geographic, taxonomic and temporal gaps through new collections,
5. Synthesize all collected information to address the above posed goals and questions.

5. The Arctic Census of Marine Life initiative: implementation and work plan

ArcCoML will comprise three major phases: a 'project building' phase (objectives 1 & 2), during which the project connections are built, data mining identifies the 'knowns' and 'knowable gaps', and available data are incorporated into OBIS. During the subsequent 'core phase' phase, the full taxonomic utilization of already collected and new field samples with a focus on the identified geographic, taxonomic and/or temporal gaps is planned (objectives 3 & 4). The third phase will be the 'synthesis phase' during which the newly accumulated data will be fully integrated into OBIS and knowledge will be synthesized, published and presented at CoML and other international meetings (objective 5), and where possible, utilized within HMAP and FMAP.

PHASE 1: PROJECT BUILDING

Objective 1: Implement an ArcCoML structure through a scientific steering group, a network of collaborating researchers and a project office

The purpose of the **Scientific Steering Group** (SSG; Table 2) is to guide ArcCoML towards the scientific goals listed above. The first international SSG meeting will be held immediately before the second ArcCoML workshop in early 2005. The SSG as it currently stands is comprised of scientists internationally known for either their Arctic/polar work and/or their expertise in a

Table 2: Scientific Steering Group for ArcCoML (alphabetical).

Name	Affiliations	Expertise	Special functions
Bodil Bluhm	University of Alaska, USA	Benthos, sea ice biota	Fairbanks office, German linkage
Don Deibel	Memorial University, Canada	Zooplankton	Integration into Canadian Arctic program (CASES)
Andrey Gebruk	Shirshov Institute of Oceanology, Moscow, Russia	Benthos, deep-sea	Russian link, MIR submersibles, MARECO link
Rolf Gradinger	University of Alaska, USA	Sea ice biota	Fairbanks office, German linkage
John Gray	Univ. of Oslo, Norway	Biodiversity	Biodiversity issues, link to Norwegian Arctic studies
Jackie Grebmeier	Univ. of Tennessee, USA	Carbon flux, benthos	Integration into US Arctic programs (SBI), Int'l Polar Year panel
Russ Hopcroft	University of Alaska, USA	Zooplankton	Fairbanks office, Plankton CoML link
Dave Kirchman	University of Delaware	Microbial ecology	Bacterial diversity and activity
Pedro Martinez	German Center for Marine Biodiversity Research	Meiofauna, taxonomy	CeDAMar link, integration into European projects
Torkel Nielson	Nat'l Environmental Res. Inst., Denmark	Zooplankton, protists	Greenland zooplankton studies
Boris Sirenko	Russian Academy of Sciences, St. Petersburg,	Benthos, shelves	Russian taxonomic center
Paul Wassmann	University of Tromsø, Norway	Arctic carbon flux, development of science plans	CABANERA link

biological realm or biodiversity research. The emphasis of the SSG is (i) to be international with regards to the leading nations in Arctic research, (ii) to provide strong biodiversity expertise, and (iii) to provide close links to other CoML projects as well as to large ongoing and planned Arctic projects, while at the same time maintaining a size that allows efficient decision-making and moderate travel costs. As ArcCoML evolves, the SSG is open to adjustment.

In addition to the SSG, we propose an **advisory board** (Table 3). The main rational for an advisory board is to maintain close contact to leaders of the large ongoing and past Arctic projects that we are hoping to build on as well as to those scientists connected to the ongoing CoML projects. As ArcCoML will have a regional rather than topical focus, we will overlap with other CoML projects focused on specific types of communities (NaGISA, CeDAMAr, ChESS, MarECO, CMarZ). We also anticipate forming strong linkages to an anticipated Antarctic CoML, and coordinating our plans for the International Polar Year (IPY) in 2007-2008 (see Appendix 1), should both programs become part of the CoML. We are still building the advisory board; it will grow and change over the lifetime of this project, as new international and national research programs will evolve, which we will aim to integrate.

Table 3: Confirmed members of the Advisory Board as of April 2004 (alphabetical).

Name	Affiliation	Special functions
William Ambrose	Bates College, USA	Arctic Ocean Transect, CASES
Ken Dunton	Univ. of Texas A&M at Austin, USA	Macroalgae, trophic diversity. GIS
Xenia Kosobokova	Shirshov Inst/ of Oceanology, Moscow, Russia	Arctic Zooplankton ecology & taxonomy
Dieter Piepenburg	University of Kiel, Germany	Greenland Sea sampling, ophiuroid genetics

An ArcCoML office, which will operate out of the University of Alaska Fairbanks, will be necessary to co-ordinate census-related efforts, connect collaborating researchers and institutes and conduct other tasks described in section 8.

Objective 2: Identify and accumulate available data

Although numerous geographic and taxonomic gaps exist in our knowledge on Arctic fauna (see above), the Arctic has been subject to explorative as well as hypothesis-driven research for over a century (Sirenko 2001). Russian scientists in particular, have a strong tradition of taxonomic work in the Arctic, but their literature is often difficult to access for most of the non-Russian nations. We plan to work collaboratively with a Russian initiative to put such data into electronic form (see Appendix 2). Additionally, a considerable body of literature exists in reports housed in various libraries and agencies existing in all Arctic nations as a result of large-scale environmental studies (e.g. due to Arctic oil and gas exploration).

It is an essential goal of this project to identify, locate, access, evaluate and, if necessary, translate these sources, in addition to journal publications, and give them a uniform format compatible with OBIS. The Arctic data need to be checked for quality, pervasive problems with synonymies resolved, and entered. The problem with synonymies and misidentifications within some taxonomic groups is massive, and seriously hampers our attempts to seek pan-arctic patterns. Although we propose a centralized Arctic portal, where possible, we will utilize and contribute the realm-specific databases developed or under development by the other realm specific CoML projects. While this work will be conducted in parallel with collection and evaluation of additional samples, an early outcome should be to fine-tune the scientific questions of ArcCoML.

PHASE 2

Objective 3: Fully analyze samples that are already available and provide taxonomic training

One of the greatest impediments to assessing biodiversity and biogeography in any region is the lack of appropriate taxonomic expertise by the ecologists who predominate many of today's research programs. This process is further complicated by differences in the taxonomic sources employed by various nations or research programs that can result in synonymies, even within common taxa. We propose to build a network of taxonomic experts and centers, especially the proposed Russian Taxonomic Center, that can help resolve such problems, through the exchange of samples and high quality images of specimens. Ultimately, as data becomes integrated into OBIS, aberrant data will become readily identifiable when viewed by the appropriate experts, who will serve to "quality control" the incoming data. Given the regional nature of this proposal, we would expect to make funds available for Arctic investigators to attend workshops by other realm specific CoML programs, or visit/exchange centers where the appropriate taxonomic expertise exists.

A significant wealth of untapped information exists in already collected materials that have not been fully examined in taxonomic detail. We intend to establish a list of such material through the ArcCoML website, and would try to foster processing of such material through small "seed monies" that might support travel or technician time.

Objective 4: Fill geographic, taxonomic and temporal gaps through new collections

While comprehensive collections have been made in the past in some areas of the Arctic, major gaps as identified in the 'unknown' section remain to be filled. These include, as described above, major portions of the Arctic deep-sea, the East Siberian shelf, microbes and protists in all realms and areas of the Arctic, winter samples, etc. In order to fill these gaps, collaborating scientists will need to apply to the appropriate funding agencies to support their research activities. Several CoML-related proposals have recently been funded such as a summer sampling cruise to the western Chukchi/Eastern Siberian Sea (including benthic, pelagic, and nekton sampling) and winter/spring sampling of sea ice biota along the Alaskan coast and on the Chukchi shelf extending into the Canada Basin. Other proposals are planned such as an expedition to the East Siberian Sea and the Canada Basin (all realms), and a significant effort targeting the IPY. If this science plan is approved, the SSG will promote the idea of ArcCoML in their respective nations and venues to make the public, the funding agencies, and the various stakeholders aware of the importance and urgency of the research, specifically in the context of the IPY 07/08. The SSG will work with the SCOR Working Group on New Technologies for Observation of Marine Life as appropriate during the planning of new projects.

PHASE 3

Objective 5: Synthesize all collected information to address the above posed goals and questions

In the last years of the ArcCoML, ~2008-2010, the collected information will be analyzed and synthesized in light of the above-formulated questions. We expect scientific publications ranging from species descriptions, to distributional maps, to latitudinal biodiversity gradient analyses. These results will also be presented by collaborating scientists at national and international meetings and be summarized in a final report to CoML/Sloan.

6. Organization and collaborations

The Arctic is bordered by Greenland (Danish), Norway, Russia, the USA and Canada, with several additional nations having long-standing traditions of Arctic research, such as Poland and Germany. It is imperative that an ArcCoML effort be international, integrated, incorporating all these nations. We propose to place the Arctic office in the Arctic at the University of Alaska Fairbanks, and form a SSG with representatives of all Arctic nations. Many of the leading institutions in the world actively involved in Arctic research are represented through members of the SSG and Advisory Board. We expect this list to grow as the program evolves.

7. Deliverables and Outreach activities

The progress and outcomes of the initial two year proposed funding effort will be determined mainly based on its documented public outreach and the achieved scientific progress.

Scientific outcomes

- Establish the ArcCoML office, and Russian Taxonomic Center
- Establish Databases linked to OBIS, with significant progress on entering existing data
- Sequences (COI – Gen bank) established for common metazoan species
- Submission and implementation of new biodiversity proposals, especially internationally coordinated proposals for the IPY
- Address major research goals as identified above
- Scientific publications(e.g. in special issues of relevant scientific/popular journals) submitted
- Newsletters circulated
- Email list-server operational
- Forum for Arctic biodiversity issues established
- 1-2 taxonomic workshops completed

These scientific goals will be achieved through coordination of all participating researchers and institutions. Database activities will largely be the responsibility of A. Pinchuk; newsletter and email list-serve will be coordinated through the other members of the office.

Outreach

- Arctic Web Portal expanded to target the public and scientists, with links to databases, images and other CoML homepages
- Promote ArcCoML at scientific meeting, in public lectures, on radio (e.g. Arctic Science Journey), and in popular magazines.
- Brochures & posters available
- Develop lesson plans in collaboration with K-12 & high school teachers
- Hands on taxonomy in classrooms

The outreach goals will, for the most part, be achieved through the Arctic office and collaborating scientists in partnership with the CoML outreach group.

8. The Arctic CoML Office

The ArcCoML office will have a variety of tasks that can be categorized into three clusters:

1. *Co-ordination of ArcCoML-related science activities.* Within ArcCoML, the office will function as the link between participating researchers and institutes by: establishing and maintaining contact among ArcCoML participants (e.g. through a newsletter and list-server), facilitating sample exchange (including HAZMAT declarations etc.), assist with data flow into OBIS and related databases, facilitating taxonomist guest visits, organizing SSG meetings etc. The office will be the link between taxonomists, field projects and the data archivist.
2. *Co-ordination of ArcCoML public relations.* The office needs to represent ArcCoML to the public by: providing information for the CoML web pages, promoting ArcCoML in the media in collaboration with Alaska Sea Grant, establishing contact with teachers to build lesson plans, organizing school class visits etc., all in conjunction with the central CoML education team. Office personnel already have experience in this respect, having helped create the Arctic Website employed by NOAA's Ocean Exploration Office (http://www.oceanexplorer.noaa.gov/explorations/02arctic/welcome.html). Presentations at relevant national/international conferences are also included under this topic.
3. *Communication with CoML.* The office will represent ArcCoML at CoML meetings, provide project updates to the CoML secretariat and communicate with the other CoML projects.

To accomplish these tasks, we propose a distributed model, with lead investigators representing each of the three arctic realms, and a Research Associate fully bilingual in English and Russian to serve as a major conduit for integration of Russian Arctic data into OBIS. Timelines and budgets to accomplish the Arctic CoML are outlines in Appendices 3 and 4.

The Russian Taxonomic center

Participation by Russian scientists is critical to the success of any Pan-Arctic program. External funds effectively facilitate on-going Russian research efforts on a regional scale as Russia remains one of the last strong holds of taxonomic expertise. We propose establishment of an Arctic Taxonomic Center ($50K pa) to utilize these talents, and provide a place where older collections can be worked up in taxonomic detail. The center will also begin entering existing Russian Arctic data into databases linked into OBIS and the ArcCoML portal. This represents an extremely cost-effect arrangement, to the overall benefit of the program. This model is similar in some respects to the NaGISA model, where both a US and Japanese office share program responsibilities.

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RESEARCH CRUISE EXPERIENCE: ~600 days at sea on cruises of 4-42 days duration aboard vessels ranging in size from 45-400 feet.

Appendix 1. The International Polar Year 2007-2008
(extracted from a draft of the U.S. National Committee)

On three occasions over the past 125 years scientists from around the world banded together to organize concentrated scientific and exploring programs in the polar regions. In each major thrust, or "year," scientific knowledge and geographical exploration were advanced, thereby extending understanding of many geophysical phenomena that influence nature's global systems. Each polar year was a hallmark of international cooperation in science. The experience gained by scientists and governments in international cooperation set the stage for other international scientific collaboration. International scientific cooperation also paved the way for several political accords that gained their momentum from the polar years. IPY 2007-2008 will expand upon this legacy of scientific achievement and societal benefits.

Environmental changes currently observed in the polar regions are unprecedented in times of modern observation, and there is concern that these rapid changes may continue or even amplify in the coming decades. The harbingers of change can be seen vividly in the polar regions. The arctic ice cover is melting, some ice shelves in Antarctica are retreating, glaciers in temperate regions are disappearing, ecosystems and vegetation patterns are changing, villages in northern Alaska are being moved to higher ground in response to rising seas, and permafrost thawing is causing the collapse of roads and buildings. Are we witnesses to an extreme in natural variability, the threshold of an abrupt change, or something more subtle? How will changes first seen in the polar regions affect us all? With increasing momentum, nations around the world are making plans for IPY 2007-2008 to attempt to answer these and many more questions.

IPY 2007-2008 will benefit society by exploring new frontiers and increasing our understanding of the key roles of the polar regions in globally linked systems. Recent technological developments give us a new ability to investigate previously unexplored areas, using new tools and new ways of looking to understand once unanswerable questions. Autonomous vehicles, genomics, and remote sensing instruments and networks are just a few of the technologies providing new approaches for studying previously inaccessible realms. The polar regions also continue to loom large in facilitating our understanding of the processes by which solar activity may seriously disturb Earth's space environment, affecting the performance of modern technologies deployed in space an on Earth. We believe that research is needed now, so that future generations may mitigate vulnerabilities and adapt to potential change.

IPY 2007-2008 is envisioned as the dawn of a new era in polar science – it will be an intense, internationally coordinated campaign that gives expanded attention to the deep relevance of the polar regions to the health of our planet, and serves to establish the ongoing observation systems and intellectual commitment needed to fully understand the polar regions and their links to the global system. It will include research in both the Arctic and Antarctic, be multi- and interdisciplinary in scope, and be truly international in participation. It will educate and excite the public and help produce the next generation of engineers, scientists, and leaders. A framework such as the IPY can provide the impetus to undertake projects that normally could not be achieved by any single nation. It allows us to think beyond traditional borders – whether national borders or disciplinary constraints – toward a new level of integrated, cooperative international science.

Appendix 4. Timeline for ArcCoML activities

Year/quarter	Meetings	New collections	Database entry	Outreach	Deliverables
Summer 2004		RUSALCA, SBI, CASES, CABANERA			
Fall 2004			begin 'old' data		
Winter 2004/5	Planning workshop SSG Meeting		entry	CoML webpage start	Begin Quarterly Newsletter, List-server
Spring 2005		Ocean Exploration Ice, SBI field collection			
Summer 2005	Taxonomic training (various venues)	Ocean Exploration All		Media contributions	
Fall 2005				Lesson plans	
Winter 2005/6	SSG Meeting			classroom present.	Interim Report
Spring 2006			start integrating		
Summer 2006		Laptev, E. Siberian Seas	new data		
Fall 2006					
Winter 2006/7					
2007		IPY activities			Interim Report
2008		IPY activities			Scientific papers
2009					Scientific papers
2010	All program meeting				Scientific papers