Mercury in Beluga Whales in the Canadian Beaufort Sea: Causes, Consequences, and Potential Research

Rosenberg[1], D.M.

Canada/Inuvialuit Fisheries Joint Management Committee
Suite 201 – 107 Mackenzie Road
P.O. Box 2120
Inuvik, NT, Canada
X0E 0T0

Canada/Inuvialuit Fisheries Joint Management Committee
Technical Report 2003-2: vi + 32 p.

[1] Freshwater Institute,
501 University Crescent, Winnipeg, MB R3T 2N6

ISSN 1709-772X

Correct citation for this publication:

Rosenberg, D.M. 2003. Mercury in beluga whales in the Canadian Beaufort Sea: causes, consequences, and potential research. Canada/Inuvialuit Fisheries Joint Management Committee Technical Report 2003-2: vi + 32 p.

CONTENTS

ABSTRACT

A workshop involving 19 participants was held on 25 October 2002 to discuss why mercury levels in beluga whales in the Mackenzie Delta and Beaufort Sea were elevated over normal in the 1990s, and to propose research that would increase our understanding of the factors involved. The Arctic Oscillation of the 1990s that affected the Canada Basin, coupled with potential atmospheric mercury depletion events during the same period, were deemed to be the most-likely climatic events of sufficiently large scale to generate enough mercury to affect belugas. Research proposals that were developed by two subgroups at the workshop included: 1) development of a physiological contaminant model for mercury in beluga; 2) retrospective analyses of beluga ages from the 1980s data; 3) updates of mercury levels in recent beluga tissue samples; 4) retrospective analyses of mercury and stable isotopes in beluga teeth and proxies for other beluga tissues; and 5) future monitoring of (a) mercury in water and suspended sediments of the Mackenzie catchment, (b) food chains in the Beaufort Sea, and (c) beluga movements in the Beaufort Sea and Amundsen Gulf. Other research recommendations that emerged during the course of the workshop included 1) the collection of mercury data from other environmental constituents of the Mackenzie catchment; 2) gathering of comparative data from other countries on beluga population biology and mercury levels; 3) the use of archived data for other ecosystem components as time series to confirm mercury levels in beluga; and 4) additions to general knowledge of mercury cycling in the Mackenzie Delta-Beaufort Sea. Two institutional recommendations were also made to improve the international flow of data among scientists examining mercury in beluga and beluga biology.

PREFACE

This report is based on a workshop held on 25 October 2002 at the Freshwater Institute. The workshop was planned and held, and the report was written, by David M. Rosenberg under contract to the Fisheries Joint Management Committee, Inuvik, NT.

Dr. Rosenberg worked for 31 years as a Research Scientist in Fisheries and Oceans Canada (DFO) on projects as diverse as the original Mackenzie Valley Pipeline Study (Berger Commission), the Churchill-Nelson river diversion, experimental reservoir creation at the Experimental Lakes Area (ELA, near Kenora, ON), and a biomonitoring system based on benthic macroinvertebrates for the Fraser River catchment in BC. He was part of research groups from the Freshwater Institute that studied 1) mercury problems resulting from the diversion of the Churchill River into the Nelson River and the flooding of Southern Indian Lake in northern Manitoba, and 2) mercury uptake and fluxes in the biota of an experimental reservoir (Lake 979) at the ELA. Dr. Rosenberg retired from DFO in September 2001, and is currently the Managing Editor of the Journal of the North American Benthological Society.

The Fisheries Joint Management Committee (FJMC) Report Series was initiated in 1986 and reports were published sporadically in a variety of formats until 1998. Information on the earlier publications can be obtained directly from the FJMC office. The Series was re-initiated in 2003 and a common format established with concurrent publication on the FJMC website (www.FJMC.ca).

INTRODUCTION

The Fisheries Joint Management Committee (FJMC) identified the need to solicit expert opinion from a number of disciplines with respect to the apparent increase in mercury levels in the beluga whale population that summers in the Canadian Beaufort Sea-Mackenzie Delta region. FJMC's concern centers around possible deleterious effects of mercury on end-users of beluga in the region.

The FJMC felt the best way to address the need for more information was to hold a one-day workshop at the Freshwater Institute. The workshop would include specialists in various areas important to the subject: climate change, permafrost, contaminants in the Beaufort Sea and in belugas, beluga population biology, fisheries, and trophic (foodweb) ecology.

The workshop had the following objectives:

I. To determine the possible sources of increasing concentrations of mercury, during the past decade, in beluga in the Mackenzie Delta. There were three hypotheses:

1. Global warming in the western Arctic has led to the melting of permafrost, releasing previously bound-up mercury. The mercury has been transported through the Mackenzie River system to the Mackenzie Delta where it has contaminated trophic pathways. Beluga are concentrating mercury as a result of their feeding activities in the Delta.
2. Mercury in the atmosphere is being deposited in the Mackenzie Delta, and beluga are concentrating it because of their feeding activities.
3. Beluga concentrate mercury in other parts of their range, and arrive in the Mackenzie Delta already carrying high concentrations.

II. To identify the research needed to either prove or disprove the three hypotheses. This objective required that the participants identify germane available data, where these data are located, and how they can be obtained. Participants would also identify new data required to test the hypotheses.

III. To identify the best strategy to obtain funding to enable work on existing data and support the generation of data needed to test one or more of the above hypotheses.

With these objectives in mind, a workshop was held on 25 October 2002 at the Freshwater Institute. Nineteen specialists drawn from management agencies, government research organizations, and universities attended (Appendix 1).

By way of introduction to the workshop, two participants were asked to present background information that would serve to inform the progress of the workshop. The first presentation, by Lois Harwood, Fisheries and Oceans Canada, Inuvik, was on the population biology of Mackenzie Delta beluga. The second presentation, by Gary Stern, Freshwater Institute, Winnipeg, was on mercury concentrations in beluga in the Canadian Arctic. Selected data from Stern's presentation are presented below.

WORKSHOP STRUCTURE AND ORGANIZATION

The original plan was to have round-table discussions following the agenda shown in Appendix 2. However, it was subsequently decided to modify time slots from 1500-1645 to consider promising research avenues more directly. The participants would break into groups to prepare research proposals using the template shown in Appendix 3 (1500-1615 h) and each group would report back on their proposals in a short plenary session (1615-1645).

This report was based on notes taken by Jennifer Shea and Nicole Nadorozny during the entire proceedings, research proposals and presentations by rapporteurs of the two groups examining promising research avenues (Appendix 4), and notes on flip charts taken sporadically through the proceedings by Burton Ayles and David Rosenberg.

Not all the discussion is presented. However, participants who made major contributions to the direction of the workshop are identified. Their contact information can be found in Appendix 1.

RESULTS AND DISCUSSION

This section of the report charts the post-presentation discussion that addressed the three original workshop objectives (see Introduction). The discussion eventually centered around two topics of quite different scale: 1) ecosystem occurrences of sufficient magnitude to account for the observed spike in mercury concentrations in beluga in the early 1990s (workshop objective #1), and 2) methodological questions concerning the original data collected (especially the 1980s data) coupled with physiological questions concerning the interaction between growth and mercury concentrations in beluga. At the end of the discussion, two subgroups (System supply/process, Methods/physiology) were formed to develop research proposals. Workshop objectives #2 and 3 are addressed in the research proposals that emerged, and are presented in the next section ("Recommended Research"). The following description charts the development of the two subgroups.

SYSTEM SUPPLY/PROCESS

The three original hypotheses were examined: 1) climate warming in the western Arctic has caused permafrost melting, which has delivered mercury via the Mackenzie River to the Mackenzie Delta-Beaufort Sea, where it is being picked up by beluga from their food; 2) atmospheric mercury from industrial emissions is being deposited in the Mackenzie Delta-Beaufort Sea; and 3) beluga concentrate mercury in other parts of their range, and bring it to the Mackenzie Delta-Beaufort Sea.

Robie Macdonald suggested we adopt the same approach as used in forensic investigations in examining these and other possible hypotheses, i.e., does an hypothesis point to a motive and an opportunity? Furthermore, the timing must be right and the critical substances must be present in the right amounts.

Macdonald presented evidence of dramatic changes in the Canada Basin that coincided with the elevated mercury levels in beluga in the early 1990s. These changes were associated with the Arctic Oscillation (AO), which is basically a quasi-periodic fluctuation in atmospheric sea-level pressure over the North Pole. Following this pressure drop in the early 1990s, changes occurred in ice-drift trajectories, seasonal clearing of ice over Arctic shelves, ice thinning/melting and diversion of freshwater runoff pathways within the interior Arctic Ocean and, perhaps, also permafrost melting (Macdonald et al. 2002, 2003). In response to these primary changes, large-scale alterations in biological composition associated with drifting ice and the upper water column of the Canada Basin also appear to have occurred (Melnikov et al. 2002). In this latter occurrence, the influx of fresh water may have produced a bottom-up change in the foodweb structure (through altering nutrient supply or even salinity of the habitat), thereby altering the exposure of beluga to mercury through their diet. Additional lower trophic levels or enhanced recycling of primary production in the upper ocean could produce an increase in mercury content of the food web, including arctic cod upon which the beluga prey. Furthermore, the alteration in the distribution of open water and the location of the ice edge could completely change the location of beluga feeding, either in where they are diving near the bottom or where they are foraging under the ice or near the ice edge. Changed carbon fluxes to the bottom could alter the uptake of mercury by benthic animals, again providing a mechanism to alter exposure of beluga to mercury through their diet when they forage near the bottom.

The changes associated with the AO could easily lead to changes in the frequency and location of mercury depletion events (MDEs), which then could alter the seasonal loading of the upper ocean with mercury during polar sunrise. In MDEs, Hg^{o} comes out of the atmosphere and is oxidized to Hg^{2+} during polar sunrise events. The Hg^{2+} is scavenged and deposited on the ice, snow, or water. The Hg^{2+} either gets reoxidized and returns to the atmosphere, or it gets into the water column where it can become methylated and bioavailable (i.e., taken up in the food chain). The process usually starts in the spring (e.g., March) and needs certain conditions (e.g., the presence of bromine in the water). Mercury depletion would potentially present a large source of mercury to be taken up in the food web.

Last, permafrost melting or catchment changes could alter the influx of material via the Mackenzie River to the Beaufort Sea, again affecting mercury cycling at least locally and perhaps regionally. Very little is known about any of these potential changes to the mercury cycle except that many system changes occurred in the late 1980s to early 1990s. The above list of changes and comments about how they affect mercury cycling clearly show the possibility of several climate-change hypotheses to explain observed recent trends in beluga mercury uptake (Macdonald et al. 2003).

The three original hypotheses were then examined in the light of this new information:

1. Hypothesis 1: Macdonald proposed that delivery of mercury from the upstream Mackenzie catchment was insufficient to explain the large increase of mercury in beluga in the early 1990s (Fig. 1). The rise of mercury levels in Ft. Good Hope burbot (Fig. 2) was minor, compared to the rise in beluga mercury levels, supporting Macdonald’s point (Drew Bodaly).

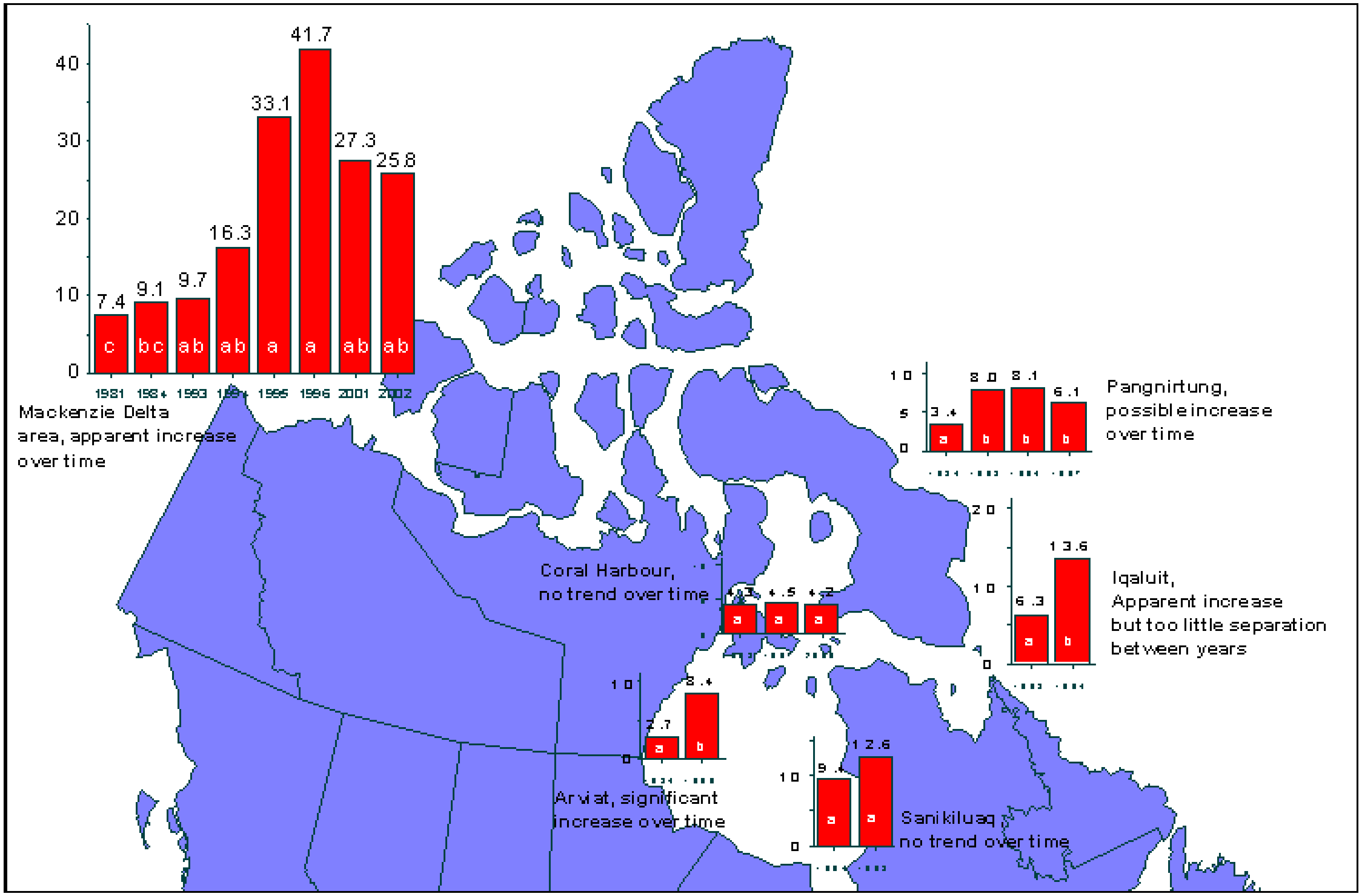

Figure 1. Mercury concentrations in beluga livers from the western Canadian Arctic and eastern Canadian Arctic (from G. Stern's presentation, 25 October 2002).

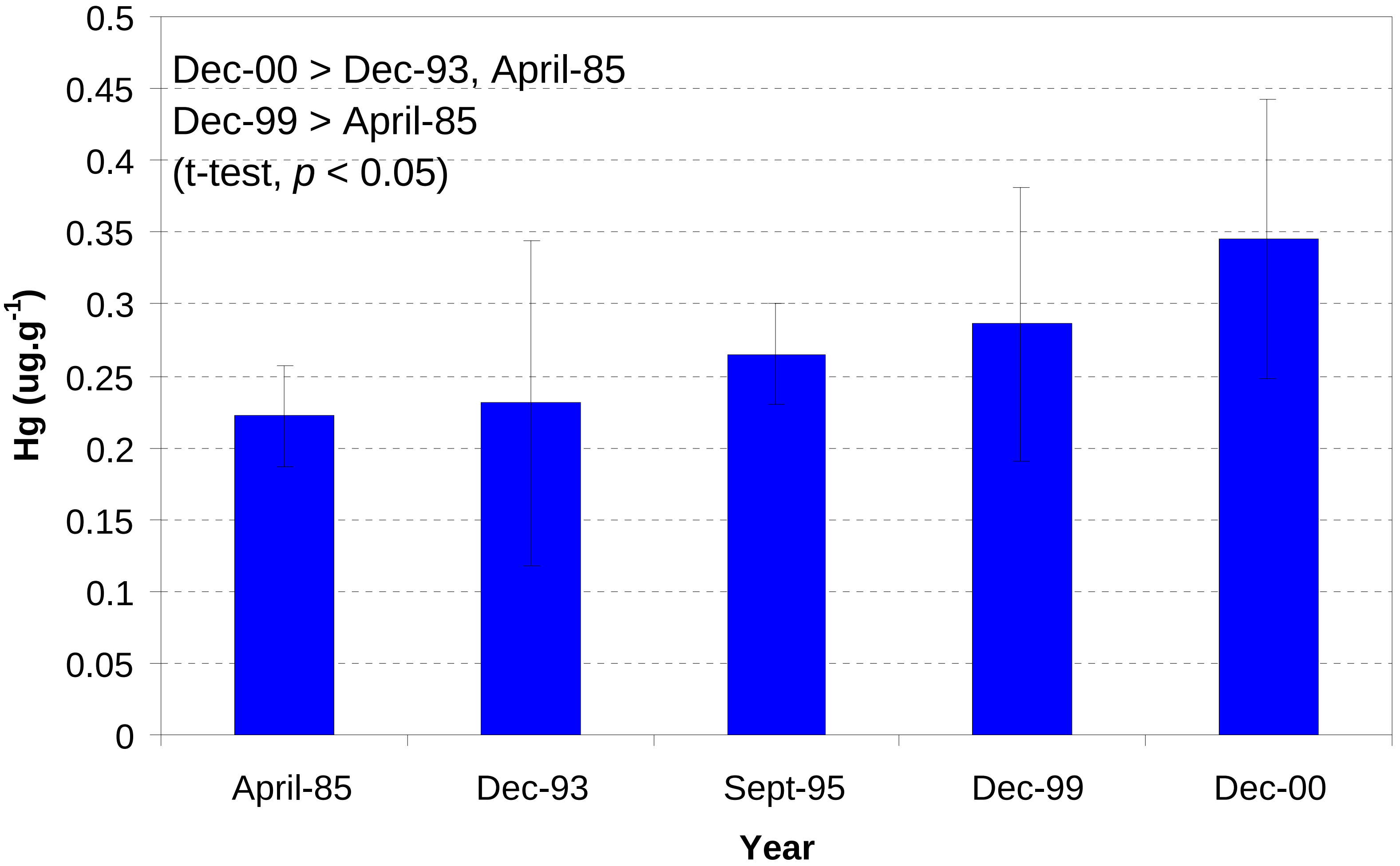

Figure 2. Mercury concentrations in the muscle of burbot from Fort Good Hope, N.W.T., 1985-2000 (from G. Stern's presentation, 25 October 2002).

Jim Reist thought that changed fish distributions and abundance may have been responsible for the rise of mercury levels in beluga. Although locally important, this change would not have been enough to affect mercury concentrations in beluga (Macdonald).

In addition, Mackenzie River flows did not change dramatically during the 1980s and 1990s (Macdonald). However, the noise in the system is large (±25%, Ray Hesslein), and we lack mercury data from a number of important environmental constituents (e.g., water, particulates, sediments), other than fish. However, it was unlikely that the Mackenzie River could deliver enough mercury into the Mackenzie Delta and Beaufort Sea to produce the increase of mercury levels seen in beluga (Macdonald).

Reist pointed out that other northern areas had ecosystem regime shifts in the mid to late 1990s, paralleling AO events in the Canada Basin (e.g., capelin in the Foxe Basin). A change in fish species composition in the northwest in the last ~30 years could be checked. Although there are no data for the Beaufort Sea, American data might be available for the Bering and/or Chukchi seas.

More data are required to support the involvement of the AO and MDEs in increasing mercury levels in beluga. However, the AO is presently relaxing, and there is a decline in recent mercury levels in beluga (Fig. 1) (Macdonald).

2. Hypothesis 2: Macdonald suggested that an industrial source of mercury (i.e., contamination) was a less likely candidate to explain recent increasing trends in beluga burdens because 1) amounts of mercury emitted from North American, European, and Japanese sources have recently been declining because of enhanced controls, and 2) industrial emissions from the USSR have declined in general over the last 15 years because of the partial collapse of industry following fragmentation of the former Soviet Union (e.g., Sirois and Barrie 1999). It is true that mercury could be mobilized from past gold-mining operations in Siberia, but these emissions would be old rather than recent, and would appear to be of insufficient magnitude to produce widespread mercury contamination in the Canada Basin, as reflected by beluga in the Beaufort Sea. The recent change in freshwater pathways associated with the AO might have initiated the input of contaminated Russian river water into the Canada Basin during the early 1990s, but there is no evidence to support such major contamination of the Russian rivers (Coquery et al. 1995). Last, it should be noted that coal is a leading source of contaminant mercury (Pacyna and Keeler 1995). China has been using increasing amounts of coal, and there are direct pathways for contaminated air masses from China to arrive in the western Arctic (Li et al. 2002).

3. Hypothesis 3: We simply do not have enough comparative data to evaluate this hypothesis. A future research aim would be to engage our colleagues in

other countries in an effort to retrieve such data, if they exist (see "Other Research Recommendations", below).

METHODS/PHYSIOLOGY

At this point in the discussion, a strong feeling emerged that a closer look at the methodological details in the past data was prudent. A second theme also emerged: the need to develop models of the relationship between growth and mercury concentrations in beluga.

Regarding methods, there were several concerns with the apparent trends in mercury concentrations. The ageing data in the 1980s results were a main source of uncertainty, and were in need of re-examination. Reist suggested an examination of methods variability vs intrinsic differences between the Beaufort Sea and elsewhere. Bodaly wondered about biases caused by seasonal sampling. (There was less concern about this potential bias than others.) Were there other sampling biases that needed to be examined? Were the statistical tests on the early data appropriate?

Regarding physiology, Hesslein suggested the usefulness of knowing what is happening to beluga physiologically (i.e., carbon appears to be respired away with age, but mercury is not). There is a need to develop models of the relationship between growth and mercury concentrations in beluga. What is the fate of mercury over time in beluga? It seems these animals retain mercury over their lifetimes. There is a need to distinguish whether increased mercury concentrations in beluga are caused by a continual exposure, or a slug/pulse of mercury over a short period. Beluga do not seem to get rid of mercury taken in as high doses over a few years. Measurements of the relationship between age and mercury concentration need to be partitioned into age groups; mercury in young beluga seems not to change, but it does in older animals. Are there regional differences in age/growth of beluga? Development of a growth model should be a priority. There is also a need to examine beluga teeth data more intensely because these data offer a time series. To summarize the physiological discussion: 1) Age analysis of the 1980s data can confirm a trend; 2) age/growth and mercury analyses may lead to a better understanding of whether we are dealing with a long-term trend (i.e., ≥50 years) or a short-term pulse of mercury; 3) teeth analyses could confirm a long-term trend or a short-term pulse in mercury; and 4) age/growth and other physiological studies could confirm regional differences and confirm trends in mercury concentrations.

At this point in the discussion, the two subgroups (see Appendix 4 for their composition) separated to develop more distinct research proposals around their areas of specialization. The groups were asked to use the template described in Appendix 3. The results of those deliberations are reported next, under "Recommended Research".

RECOMMENDED RESEARCH

The Methods/physiology and System supply/process subgroups both produced four potential research proposals (summarized in Appendix 5). The research proposal template (Appendix 3) was not always used, so the description here will follow a narrative style.

METHODS/PHYSIOLOGY SUBGROUP

1. Development of a physiological contaminant model – This proposal would be led by Ray Hesslein, with Gary Stern and Lois Harwood as co-proponents. Basically, the proposal is meant to develop the mercury/growth model discussed above. The model would determine if the mercury signal detected in beluga is real, and seeks to identify the physiological basis of high mercury concentration in beluga. The intent is to define model parameters and their variabilities, and use sensitivity analyses to test what may have caused the observed patterns (i.e., a spike in mercury concentrations over a few years vs constant levels). The fish mercury model (e.g., Ross Norstrom's) could be used as a basic approach, and modified by using mammalian models (e.g., rabbit). The model would be individual-based, with separate pools to represent organs. There would be statistical modeling of populations using estimates of age/sex classes. Development of the model is expected to take one year and cost $25,000-30,000. This amount would be equivalent to six months of postdoctoral time plus expenses. Canadian Arctic Shelf Exchange Study (CASES) and FJMC would be possible funding sources.

2. Retrospective analyses of ages from beluga collections – No specific leader for this proposal was identified (although post-workshop discussions revealed that Stern was willing). Co-proponents could include Patt Hall (DFO, Freshwater Institute), Barb Stewart (biological consultant, Winnipeg), and Blair Dunn (DFO, Freshwater Institute). The proposal is meant to validate the 1980s data by correcting for age of the belugas (i.e., is the mercury signal still real with corrected ages?). Age-corrected 1988-1994 data could then be compared to 2000, 2001, etc. data. The expected costs for this proposal would be low ($~5000-10,000). Possible funding sources would include FJMC and DFO. (Post-workshop discussions with Stern revealed that the research in this proposal was underway).

3. Mercury levels over time as determined from beluga tooth layers (time-series analysis) – This proposal was essentially the same as proposal #1 of the System supply/process subgroup (see below), so it won't be repeated here. The fact that both subgroups recommended the same proposal indicates some degree of priority for this research.

4. Update of mercury in most recent samples – This proposal would be led by Gary Stern; no co-proponents were identified. The purpose of this proposal is to monitor mercury levels in beluga in the 2000s. Do mercury levels continue to be elevated, or are they coming down? Is the decline noted in 2001 samples (Fig. 1) real? Also, an attempt would be made to identify changes in beluga feeding over time. The methods include mercury analyses on recent beluga collections, stable isotope analyses on beluga over the entire time period of beluga collections (e.g., 1980-present for teeth), and mercury and stable isotope analyses of beluga prey, whenever available. Mercury analyses of 2003 samples are expected to cost $25,000.

In a post-workshop discussion with Stern, he pointed out that the number-one priority should be continued monitoring of beluga tissues over the next decade for mercury (total and methyl), other metals like selenium, and stable isotopes (see below for more detail). He also pointed out that much of the retrospective analyses identified above had already been done.

SYSTEM SUPPLY/PROCESS SUBGROUP

This subgroup produced four proposals, one based on retrospective analyses and three based on future monitoring activities. (The subgroup tacitly recognized that organizations like FJMC could not be directly involved in potential large-scale international endeavours like monitoring the AO. The proposals are more specific, but still recognize the large-scale factors likely to influence mercury levels in beluga.)

1. Retrospective analyses – No leader was identified for this proposal, although Peter Outridge, and co-proponents Keith Hobson and Brent Wolfe, were identified in Methods/physiology proposal #3. The first part of the proposal would examine stable isotopes and mercury in teeth of beluga to detect mercury levels over time and correlate them with changes in prey (carbon and nitrogen isotopes) and hydrological conditions (oxygen isotopes to differentiate between marine and freshwater sources). Tooth samples could be divided into those post-1980s and those pre-1980s, the latter retrieved from middens. The initial frequency of analysis should be fine enough (i.e., seasonal or semi-annual) to calibrate the data (e.g., can signals be detected in a common part of the tooth?, can seasonal signals be detected?) followed by longer analytical periods (e.g., biennial). Less frequent measurements (e.g., of tooth growth) are, of course, cheaper than more frequent ones.

   The subgroup encouraged examination of Alaskan samples (not the Pt. Lay population because it feeds in the Beaufort Sea). Soft tissues would be done first, followed by tooth samples. The Geological Survey of Canada was identified as a possible funding source in Methods/physiology proposal #3, although no dollar level was assigned to the proposal.

   The second part of the proposal concerned examination of proxies to see if similar mercury and stable isotope signals can be detected in archived samples from Canada and Alaska. These proxies include bowhead balleen (considerable data already exist in Don Shell's work), seal teeth, cisco and arctic cod, and bird feathers.

   (The use of proxies was also a theme of the post-presentation discussions. It was felt that ringed seals may be proxies for beluga, but bowhead whales represent a different trophic level. Feathers from benthic- or pelagic-feeding birds may be valuable, as would be the use of fish scales. The general feeling of the workshop participants was that the development of proxies for the mercury content in belugas should be encouraged.) The subgroup did not identify either a budget or possible funding sources for this part of the proposal.

2. Future monitoring: mercury in water and suspended sediments – No leader was identified for this proposal (although Stern would be a possibility). The object of this proposal is to determine the form of mercury (total, methyl) in fresh water and marine water and suspended sediment, and to determine the importance of the Mackenzie River in transporting mercury to the Mackenzie Delta and the Beaufort Sea. ^{18}O isotope could be used to distinguish between freshwater and marine sources. Initial sampling would be intense over space and time to judge variability of the data (e.g., pulses in space and time); later sampling could be diminished based on initial results.

   Stern is already doing this research as part of CASES. His sampling begins at Hay River and extends through the estuarine zone to the Beaufort Sea. He is already sampling in all four seasons in the Beaufort Sea, but only in summer (July) in the Mackenzie River. He could extend the Mackenzie River sampling to all four seasons as well, but did not provide an estimate of incremental costs for this expansion.

   A post-workshop discussion with Stern also revealed that he and his colleagues are planning to measure total and methyl mercury and examine biogeochemical processes in a series of permafrost cores collected from the Mackenzie catchment. These data will help identify sources and potential loads of mercury being delivered by the Mackenzie River to the Mackenzie Delta and Beaufort Sea.

3. Future monitoring: foodchains in the Beaufort Sea – No leader was identified for this project (although Jim Reist would be a possibility), and no costs were assigned. The intent of this proposal would be to archive time series of foodchain samples for future analysis. Foodchain items (not specified) would be collected from nearshore, offshore, pelagic, and benthic habitats of the Beaufort Sea, in areas occupied by beluga. Optimally, samples would also be collected from the western Chukchi and Bering seas, where beluga spend part of the year. CASES would be a suitable sponsor for these studies, although the CASES program is scheduled to end in several years. (CASES would also be well placed to study MDEs, which usually occur in spring.) The Beringia Project is another prospective (and perhaps more long-term) sponsor.

4. Future monitoring: beluga tracking and TDR (time-depth recorder) – No leader was identified (although Pierre Richard is the best possibility), and no cost estimates were provided. The intent of this proposal is to provide a full 12-month cycle of habitat use by beluga (there are no data from winter and spring), and to provide more dive data in summer and autumn to better understand the use of the Beaufort Sea and Admundsen Gulf (i.e., is activity in either place benthic or pelagic?). Richard has several current proposals, but did not elaborate on possible sponsors for this research.

OTHER RECOMMENDATIONS

This section addresses worthy institutional and research recommendations that resulted either from the workshop or in post-workshop discussions (summarized in Appendix 5). The research recommendations were not formally proposed by either of the subgroups.

INSTITUTIONAL RECOMMENDATIONS

Two recommendations would enable the FJMC to coordinate much of the research discussed in the workshop. These recommendations came from post-workshop discussions with Ray Hesslein.

1. Hire a post-doctoral-level coordinator to undo some of the knots that exist in Canadian, US, and Russian data. It was obvious, from the workshop, that data on beluga and the mercury levels they carry are quite scattered. Someone is needed who can draw together these disparate data sources.

2. Establish a committee of international experts to ensure a flow of data among groups addressing similar beluga problems. This committee could also be responsible for holding yearly workshops to exchange data. In his opening comments to the workshop, Robert Bell asked the participants to maintain an international perspective in their discussions, and mentioned that the FJMC had an international role to play. This recommendation would be an ideal FJMC involvement.

RESEARCH RECOMMENDATIONS

The research recommendations fell into four general groupings: 1) mercury data from the Mackenzie River catchment, 2) comparative data on beluga population biology and mercury levels, 3) the use of archived data as time series, and 4) additions to general knowledge. These four groups are discussed next:

1. Mercury data from the Mackenzie River catchment. – There was general agreement that only large-scale climatic/oceanographic events could change ecosystems enough and provide sufficient mercury to cause the increases seen in beluga, but participants were still bothered by the lack of mercury data from environmental constituents in the Mackenzie River catchment. The availability of these data would prove (or disprove) the Mackenzie catchment as a significant source of mercury to the Mackenzie Delta-Beaufort Sea. To this end, there is a need for measurements of mercury concentrations in water (especially), particulates, sediments, insects, and fish from all over the Mackenzie catchment (see "Recommended Research", "System supply/process", proposal #2). Some of these data may be retrieved from already archived samples (see below). These data should be stratified spatially and temporally.

2. Comparative data on beluga population biology and mercury levels. – The participants recognized the need for better cooperation with Alaskan and Russian workers in the areas of population migrations, feeding, and mercury contamination. Although not much hope was held out for the existence of Russian data, Alaskan data should be plentiful (e.g., the existence of a US marine tissue bank was mentioned). Do beluga sampled in the Bering and Chukchi seas exhibit the same time course and degree of mercury concentrations as Beaufort Sea populations? Are feeding habits in the Bering, Chukchi and Beaufort seas similar (see "Recommended Research", "System supply/process", proposal #3)? Can any difference be used to explain differences in mercury levels? Has there been a major change in prey fish distributions that could lead to increased mercury levels in any of these geographic

locations? Last, is there evidence from locations other than the Canada Basin for regime shifts in ecosystem processes (e.g., changes in abundance of prey items for beluga) that parallel oceanographic shifts caused by large-scale events such as the AO? The institutional recommendations given above can help resolve these questions.

3. The use of archived data as time series. – Time-series data would be useful to determine whether other ecosystem components were reflecting similar changes in mercury levels to those observed in beluga in the Beaufort Sea. For example, archived data from other geographic locations may be useful to check the effects of the AO on a wider scale than just the Canada Basin (see above) (Reist). There is a set of cores from 40 lakes in the Mackenzie Delta that could be used to check the time course of mercury (Lyle Lockhart). A large number of cisco from the Mackenzie catchment has been archived (Reist). (See also "Recommended Research", "System supply/process", proposal #1).

4. Additions to general knowledge. – Better understanding of how mercury cycles through the Mackenzie Delta-Beaufort Sea is needed. Studies that address parts of this general need deserve support, but should be coordinated by the committee of experts mentioned in institutional recommendation #2 above. Strong direction is needed to keep general-knowledge studies on track.

ACKNOWLEDGEMENTS

I thank the people listed in Appendix 1 for participating in the workshop and answering requests for information and clarification useful in preparing this report. N. Nadorozny and J. Shea kindly provided their notes from the workshop. R. Hesslein, R. Macdonald, J. Reist, P. Richard, and G. Stern checked the accuracy of the content of some parts of the report. R. Macdonald was especially helpful in providing an accurate account of his comments on the AO and MDEs. G. Stern provided useful comments throughout the preparation of the report. The FJMC provided support for this contract, and refreshments during the workshop. The FJMC also aided some participants with travel expenses. I thank DFO, Winnipeg, for providing the facilities for holding the workshop.

LITERATURE CITED

Coquery, M., D. Corsa, and J.M. Martin. 1995. The distribution of dissolved and particulate mercury in three Siberian estuaries and adjacent coastal waters. Water, Air and Soil Pollution 80: 653-664.

Li, Y.-F., R.W. Macdonald, L.M.M. Jantunen, T. Harner, T.F. Bidleman, and W.M.J. Strachan. 2002. The transport of β-hexachlorocyclohexane to the western Arctic Ocean: a contrast to α-HCH. Science of the Total Environment 291: 229-246.

Macdonald, R.W., T. Harner, and J. Fyfe. 2003. The interaction of climate change on contaminant pathways to and within the Canadian Arctic. Pages 221-275 *in* T.F. Bidleman, R.W. Macdonald, and J. Stow (editors). The Canadian Arctic Contaminants Assessment Report II. Department of Indian Affairs and Northern Development, Ottawa.

Macdonald, R.W., F.A. McLaughlin, and E.C. Carmack. 2002. Freshwater and its sources during the SHEBA drift in the Canada Basin of the Arctic Ocean. Deep-Sea Research II 49: 1769-1785.

Melnikov, I.A., E.G. Kolosova, H.E. Welch, and L.S. Zhitina. 2002. Sea ice biological communities and nutrient dynamics in the Canada Basin of the Arctic Ocean. Deep-Sea Research I 49: 1623-1649.

Pacyna, J.M., and G.J. Keeler. 1995. Sources of mercury to the Arctic. Water, Air and Soil Pollution 80: 621-632.

Sirois, A., and L.A. Barrie. 1999. Arctic lower tropospheric aerosol trends and composition at Alert, Canada: 1980-1995. Journal of Geophysical Research 104: 11599-11618.

APPENDIX 1: ATTENDEES AT THE WORKSHOP ON MERCURY IN BELUGA IN THE MACKENZIE DELTA, 25 OCTOBER 2002, FRESHWATER INSTITUTE, WINNIPEG, MB.

Ayles, B.
Fisheries Joint Management Committee
255 Egerton Avenue
Winnipeg, MB R2M 2X3
204-257-4453
204-257-4453 (fax)
aylesb@escape.ca

Bell, R.
Fisheries Joint Management Committee Chair
Inuvialuit Renewable Resource Committees
P.O. Box 2120
Inuvik, NT X0E 0T0
867-777-2828
867-777-2610 (fax)
fjmc@jointsec.nt.ca
robert.bell@sk.sympatico.ca

Bill, K.
Resource Biologist
Fisheries Joint Management Committee
Box 2120
Inuvik, NT X0E 0T0
867-777-2828
867-777-2610 (fax)
fjmc@jointsec.nt.ca
tech-rp@jointsec.nt.ca

Bodaly, D.
Research Scientist
DFO, Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6
204-983-5218
204-984-2404 (fax)
bodalyd@dfo-mpo.gc.ca

Nadorozny, N.
Department of Biological Sciences
University of Calgary
2500 University Drive NW
Calgary, AB T2N 1N4
403-220-3125
403-289-9311 (fax)
ndnadoro@ucalgary.ca

Outridge, P.
Research Scientist
Geological Survey of Canada
601 Booth Street
Ottawa, ON K1A 0E8
613-996-3958
613-943-1286 (fax)
outridge@nrcan.gc.ca

Richard, P.
Research Scientist
Arctic Research Division
DFO, Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6
204-983-5130
204-984-2403 (fax)
richardp@dfo-mpo.gc.ca

Reist, J.
Research Scientist
Arctic Research Division
DFO, Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6
204-983-5032
204-984-2403 (fax)
reistj@dfo-mpo.gc.ca

Dick, T.
Department of Zoology
University of Manitoba
Winnipeg, MB R3T 2N2
204-474-9896
204-474-7588 (fax)
tadick@ms.umanitoba.ca

Ferguson, S.
Research Scientist
DFO, Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6
204-983-5057
204-984-2403 (fax)
fergusons@dfo-mpo.gc.ca

Harwood, L.
Stock Assessment Biologist
Fisheries and Oceans Canada
Suite 201 Diamond Plaza
5204-50th Avenue
Yellowknife, NT X1A 1E2
867-669-4916
867-669-4941 (fax)
harwoodl@dfo-mpo.gc.ca

Hesslein, R.
Research Scientist
DFO, Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6
204-983-5251
204-984-2404 (fax)
hessleinr@dfo-mpo.gc.ca

Lockhart, L.
Scientist Emeritus
DFO, Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6
204-832-2878
llockhart@shaw.ca

Rosenberg, D.
Scientist Emeritus
DFO, Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6
204-983-5253
204-984-2404 (fax)
rosenbergd@dfo-mpo.gc.ca

Shea, J.
Arctic Institute of North America
University of Calgary
2500 University Drive NW
Calgary, AB T2N 1N4
403-282-9294
jashea@ucalgary.ca

Stern, G.
Research Scientist
Arctic Research Division
DFO, Freshwater Institute
501 University Crescent
Winnipeg, MB R3T 2N6
204-984-6761
204-984-2403 (fax)
sterng@dfo-mpo.gc.ca

Wolfe, B.
Department of Geography and
Environmental Studies
Wilfred Laurier University
75 University Avenue West
Waterloo, ON N2L 3C5
519-884-0710, ext. 3470
bwolfe@wlu.ca

Wright, F.
Research Scientist
Geological Survey of Canada
601 Booth Street
Ottawa, ON K1A 0E8
613-996-9324 613-943-0580 (fax)
fwright@nrcan.gc.ca

Macdonald, R
Research Scientist
DFO, Institute of Ocean Sciences
P.O. Box 6000
Sidney, BC V8L 4B2
250-363-6409
macdonaldrob@pac.dfo-mpo.gc.ca

APPENDIX 2: ORIGINAL AGENDA FOR THE WORKSHOP ON MERCURY IN BELUGA IN THE MACKENZIE DELTA, 25 OCTOBER 2002, FRESHWATER INSTITUTE, WINNIPEG, MB.

AGENDA
WORKSHOP ON MERCURY IN BELUGA IN THE MACKENZIE DELTA
25 OCTOBER 2002
0830-1700 HR
FRESHWATER INSTITUTE (SMALL SEMINAR ROOM)
501 UNIVERSITY CRESCENT
WINNIPEG, MB
R3T 2N6

0830-0850 – Opening of the Workshop (welcome by Robert Bell and David Rosenberg) and introductions

0850-0930 – Presentations (15 min and 5 min question period for each):
Biology and distribution of beluga – Lois Harwood
Contaminants in beluga – Gary Stern

0930-1015 – Discussion of Objective 1 (possible hypotheses regarding sources of mercury in beluga)

1015-1030 – Break

1030-1115 – Continue discussion of Objective 1

1115-1200 – Discussion of Objective 2 (sources of extant data and further research needed to test hypotheses)

1200-1230 – Lunch (served in small seminar room)

1230-1315 – Continue discussion of Objective 2

1315-1445 – Discussion of Objective 3 (possible sources of funding to support use of extant data and generate new data)

1445-1500 – Break

1500-1600 – Discussion of future possible collaborative research

1600-1645 – Written responses to 3 original objectives

1645-1700 – Workshop wrap-up: Burton Ayles

APPENDIX 3: TEMPLATE FOR RESEARCH PROPOSALS TO BE USED AT THE WORKSHOP ON MERCURY IN BELUGA IN THE MACKENZIE DELTA, 25 OCTOBER 2002, FRESHWATER INSTITUTE, WINNIPEG, MB.

MERCURY IN BELUGA RESEARCH PROPOSAL

TITLE

AUTHORS AND THEIR DISCIPLINES

DESCRIPTION OF RESEARCH

Hypothesis(es) being tested

Methods (including data repositories/sharing and equipment/facilities required)

Timelines for completion of research

BUDGET

Capital

Salaries

O & M in field and laboratory

PARTNERS

POSSIBLE FUNDING SOURCES

DELIVERABLES/EXPECTED PRODUCTS

OTHER COMMENTS

APPENDIX 4: MEMBERS OF THE TWO SUBGROUPS THAT DEVELOPED RESEARCH PROPOSALS AT THE WORKSHOP ON MERCURY IN BELUGA IN THE MACKENZIE DELTA, 25 OCTOBER 2002, FRESHWATER INSTITUTE, WINNIPEG, MB.

A: METHODS/PHYSIOLOGY

B. Ayles
K. Bill
D. Bodaly
S. Ferguson
L. Harwood
R. Hesslein
L. Lockhart
N. Nadorozny
G. Stern

B: SYSTEM SUPPLY/PROCESS

T. Dick
R. Macdonald
P. Outridge
J. Reist
P. Richard
D. Rosenberg
J. Shea
B. Wolfe
F. Wright

APPENDIX 5: SUMMARY OF RESEARCH RECOMMENDATIONS STEMMING FROM THE WORKSHOP ON MERCURY IN BELUGA IN THE MACKENZIE DELTA, 25 OCTOBER 2002, FRESHWATER INSTITUTE, WINNIPEG, MB, OR FROM POST-WORKSHOP DISCUSSIONS.

TABLE 1: RESEARCH RECOMMENDED BY THE TWO WORKSHOP SUBGROUPS

TITLE	RATIONALE	COMMENTS
METHODS/PHYSIOLOGY SUBGROUP		
Development of a physiological contaminant model	To develop a mercury/growth model to determine if the mercury signal in beluga is real and to identify the physiological basis of high mercury levels in beluga	Pre-existing mercury models (e.g., for fish) would be adapted; contact persons: Ray Hesslein, Gary Stern, Lois Harwood; expected duration: 1 y; expected cost: $25,000-30,000; possible funding sources: CASES, FJMC
Retrospective analysis of beluga ages	To validate the 1980s mercury data in beluga by correcting for ages	Possible contact persons: Pat Hall, Barb Stewart, Blair Dunn; expected cost: $5,000-10,000; possible funding sources: DFO, FJMC
Mercury levels over time as determined from beluga teeth	(See first entry, next section)	

Update of mercury levels in recent beluga samples	To monitor mercury levels in beluga in the 2000s	Is the decline in the 2001 samples real? Contact person: Gary Stern; expected cost $25,000; possible retrospective mercury and stable isotope analyses also proposed for beluga and prey
SYSTEM SUPPLY/PROCESS SUBGROUP		
Retrospective analyses		
•. Mercury and stable isotopes in beluga teeth	To detect mercury levels over time and correlate them with changes in hydrological conditions and prey	Tooth samples to be divided into pre- and post-1980s; use of Alaskan samples encouraged; contact persons: Peter Outridge, Keith Hobson, Brent Wolfe; possible funding source: GSC
• Examination of proxies	To determine if similar mercury and stable isotope signals can be detected from archived samples in Canada and Alaska	Proxies include bowhead balleen, seal teeth, cisco, arctic cod, fish scales, bird feathers
Future monitoring		
• Mercury in water and suspended sediments	To determine the form of mercury in fresh and marine water and suspended sediments, and the	Initial sampling to be intense over space and time; later sampling to be adjusted; contact person:

	importance of the Mackenzie River in transporting mercury to the Mackenzie Delta and Beaufort Sea	Gary Stern who is already partially involved in doing this research through CASES
• Foodchains in the Beaufort Sea	To archive foodchain samples for future analyses	Collections to be stratified according to habitat in areas occupied by beluga; western Chukchi and Bering seas included, optimally; possible contact person: Jim Reist; possible funding sources: CASES, Beringia Project
• Beluga tracking and TDR (time-depth recorder)	To provide data on the annual cycle of habitat use by beluga	Better understanding of the use of the Beaufort Sea and Amundsen Gulf; contact person: Pierre Richard

31

TABLE 2: OTHER RESEARCH RECOMMENDATIONS

TITLE	RATIONALE	COMMENTS
Mercury data from the Mackenzie River catchment	There is a need for data on mercury levels in environmental constituents to identify the importance of the Mackenzie catchment as a source of mercury to the Mackenzie Delta/ Beaufort Sea	Includes mercury levels in water, particulates, sediments, benthic invertebrates, and fish; archived samples also to be used; spatial and temporal stratification of samples recommended
Comparative data on beluga population biology and mercury levels	There is a need for comparative data on population migrations, feeding, and mercury levels in beluga in the Beaufort, Bering, and Chukchi seas to determine if mercury levels in the Beaufort Sea are unusual	Have large-scale events such as the Arctic Oscillation (AO) caused regime shifts (e.g., changes in prey) elsewhere?
Use of archived data as time series	Do other ecosystem components reflect similar changes in mercury levels to those observed in beluga in the Beaufort Sea?	Cores from 40 lakes in the Mackenzie Delta; archived cisco from the Mackenzie catchment; other archived data from elsewhere to check effects of AO

Additions to general knowledge	Promotes better understanding of mercury cycling through the Mackenzie Delta/Beaufort Sea	Mercury/growth model development (Table 1) is an example

32