IMPACTS OF CHANGES IN SEA ICE AND OTHER ENVIRONMENTAL PARAMETERS IN THE ARCTIC

FINAL REPORT OF THE MARINE MAMMAL COMMISSION WORKSHOP GIRDWOOD, ALASKA, 15-17 FEBRUARY 2000

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Workshop
To bring together scientists and indigenous experts to discuss the many signs of change in the Arctic environment, the Marine Mammal Commission held a workshop on Impacts of Changes in Sea Ice and Other Environmental Parameters in the Arctic. The combination of multi-disciplinary science and traditional knowledge made a strong and urgent case for addressing the challenges posed by environmental change in the Arctic. Although the workshop focused largely on the Alaskan Arctic, its implications are international in scope, as all Arctic regions face similar challenges related to environmental change.

The workshop was held 15-17 February 2000 in Girdwood, Alaska. The number of participants in the workshop was limited, and chosen to provide a balance between scientists and indigenous experts, and among areas of expertise. The purposes of the workshop were:

- to review, from both traditional knowledge and scientific perspectives, how changes in sea ice and other environmental parameters may be affecting Arctic living resources and the indigenous cultures and practices that depend on those resources,
- to identify possible measures that can be taken to mitigate the impacts of realized and anticipated changes, and
- to develop a document that provides a compelling blueprint for action for legislators, conservationists, Arctic residents, and others.

This final report contains the conclusions and recommendations of the workshop, a summary of the discussions held by break-out groups during the workshop, and papers describing various aspects of environmental change in the Arctic.

Conclusions
In Arctic Alaska, there are many indications of significant environmental change over time. Such changes are not merely curiosities from a remote area. They have severe impacts on the lives of residents of northern Alaska, most of whom are Alaska Natives pursuing traditional ways of life deeply rooted in the local environment. The changes seen in the Arctic are the early signs of changes in climate that are likely to affect much of the world in the next several decades. The impacts to Arctic residents and the lessons those impacts have for the rest of the country and the world are ignored at our peril. It is clear that more attention is needed to assess the risks that we face and to identify actions that can be taken to minimize those risks.

In considering what is known today and what needs to be done, workshop participants made a number of observations on the state of our knowledge and its applicability to the responses that might be made to the impacts of climate change:

- There are significant disconnects among scientific disciplines. More attention is needed to the species that affect people directly.
- Policy makers give too little attention to environmental change.

- Better information is needed about specific regional scenarios for changes in sea ice, especially for helping to identify potential impacts to communities.
- More systematic use should be made of the expertise that Alaska Natives have in observing the environment, extending back many decades in personal memory and farther in what has been handed down from past generations.
- Subsistence hunting, fishing, and gathering are vital and irreplaceable activities for Alaska Native communities, but it is difficult or impossible to express their full significance.

A common thread to these and other discussions during the workshop was that climate change is a far-reaching threat to coastal communities. It is essential that such communities be involved in research and policy concerning environmental change. In this regard, workshop participants had a number of observations on the process of research:

- Collaborative research between communities' members and outside scientists requires continuity and time to build trust, train personnel, and learn to understand the perspectives and expectations of the various partners.
- Community-based programs should be coordinated or integrated so that the communities can make best advantage of the programs in which they participate.
- Research needs to involve young people, especially through schools.
- Progress requires dedicated individuals, not just good ideas.
- Research involving the participation of local researchers must adequately compensate those participants.
- The use of scenarios must be done sensitively, especially with "worst-case" predictions about the future of specific communities.

Recommendations

Workshop participants listed a number of recommendations in several categories, listed below, plus two overarching recommendations emerged:

- *Promote long-term commitments*, especially for collaborative research that requires recruiting and training local researchers.
- *Take better advantage of existing programs*, including those that are already active in Arctic communities and those that upon which community-based research can be built.

<u>Research</u>

- *Develop a formal plan for recording systematic observations by residents of coastal communities*. A team of scientists and local observers should determine which measurements are appropriate for gathering by local observers and which factors are significant from the local perspective.
- *Develop a system for reporting other noteworthy events*. In addition to observations of regular phenomena, unusual events such as strandings and die-offs are worth recording and analyzing.
- *Promote the creation of better baselines of data*. Existing baseline data are often from too few monitoring sites or over timelines that are too short. Effective monitoring

requires archiving of data as well as ready access to those data for analyses and comparisons.

- *Document Native observations of environmental change*. The systematic documentation of Native knowledge can help identify patterns in the environment over time, helping sort out short- and long-term changes.
- *Develop more detailed local scenarios for assessing the potential impacts of climate change*. While firm predictions are beyond our reach, more details about the range of likely effects would help generate more plausible scenarios from which responses could be planned.
- *Make more use of integrative tools for analyzing data*. In part this is a question of data access, but it is also a matter of having tools that allow researchers to integrate various data sets to prepare complex analyses.
- *Allow time for the creation of real partnerships between communities and researchers*. Where possible, time and perhaps funding for the development of real partnerships should be given.
- *Explore ways to make use of climate change*. Some effects of climate change may provide opportunities for alternative energy or for new patterns of resource use.

<u>Policy</u>

- *Address the causes of climate change*. From a policy perspective, we need a greater willingness to examine the range of human actions that affect climate change and to develop means of changing our actions to minimize their impacts.
- *Recognize actual and potential problems*. Ignoring the warning signs of climate change will only lead to far greater costs in the future, when problems become crises.
- *Provide intrinsic valuations for natural resources*. Alternative means of valuing natural resources should be developed so that activities such as subsistence that are largely outside the cash economy are properly reflected in damage calculations.
- *Assess institutional cultures that prevent meaningful change*. Understanding the nature of those institutional cultures is essential to identifying ways to bring about effective and timely responses to threats such as those posed by climate change.

<u>Communication</u>

- *Develop better ways to communicate results to Native communities*. Good communication should take into account Native ways of thinking and communicating, for example through visual and oral media rather than only in writing.
- *Provide training in communication*. Communication should stimulate curiosity and convey the excitement of science, which will help attract greater interest among community members, especially young people.
- *Consider a variety of means for communicating*. Local radio programs, regional newspapers, public lectures, mailings to community residents, and posters are among the many ways that can be used to communicate with affected groups.
- *Teach scientists, agency personnel, and others about Native cultures*. Written materials and in-person orientation sessions are among the ways that newcomers can be introduced to the ways of a community.

- *Teach community members about science and scientists*. In addition to introducing community members to scientists, such training should include an introduction to scientific methods and theories.
- *Review web-based programs to develop new ideas*. The web can be used for data management and access, and for frequent communication between researchers within and outside the community.
- *Promote professional recognition for the importance of communicating*. Giving professional recognition to efforts to give results back to communities would help encourage greater effort in communicating effectively and often.

<u>Education</u>

- *Develop general curricula on climate change and our connection to the environment*. Curriculum materials that can help explain and demonstrate both will create a better-informed citizenry.
- *Develop specific curriculum materials to show the local context of climate change*. Generalizations about climate change should be supplemented with specific local information to help students see how climate change may affect them and their home regions.
- *Promote interactions among schoolchildren from different places*. Sharing local experiences and observations with students from other parts of the country or world can help students learn more about others and more about the different ways that climate change affects various parts of the globe.
- *Make use of existing programs that involve students and teachers in research*. Such programs can help with education as well as communication, helping researchers become more involved in the communities in which they work.

INTRODUCTION

There are many signs of change in the Arctic environment. Some, such as thinning of sea ice, earlier growing seasons on land, and rising temperatures in permafrost, have been identified through scientific research. Others, such as changes to sea ice characteristics, poor body condition of some marine mammals, and a greater frequency of extreme weather, have been noted by indigenous residents of the Arctic. With these observations in mind, and with a desire to bring together scientists and indigenous experts to discuss them, the Marine Mammal Commission held a workshop on Impacts of Changes in Sea Ice and Other Environmental Parameters in the Arctic, funded by the University of Alaska's North Pacific Marine Research Initiative, the National Oceanic and Atmospheric Administration's Office of Oceanic and Atmospheric Research, and the National Marine Fisheries Service. The combination of multi-disciplinary science and traditional knowledge, unusual in itself, made a strong and urgent case for addressing the challenges posed by environmental change in the Arctic. Although the workshop focused largely on the Alaskan Arctic, its implications are international in scope, as all Arctic regions face similar challenges related to environmental change.

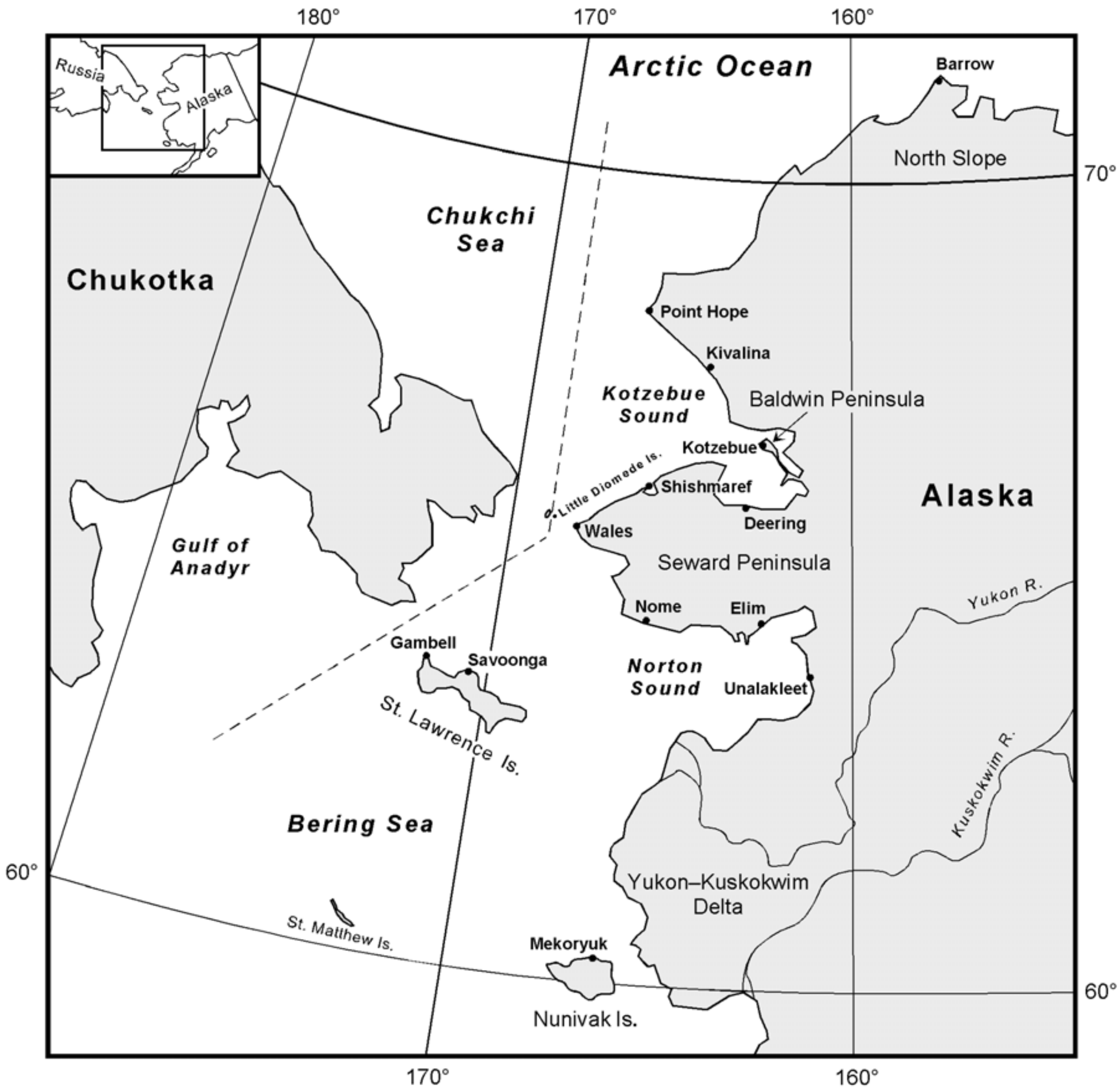
The workshop was held 15-17 February 2000 in Girdwood, Alaska. The number of participants in the workshop was limited, and chosen to provide a balance between scientists and indigenous experts, and among areas of expertise. The participants are listed at the end of this report. The purposes of the workshop were:

- to review, from both traditional knowledge and scientific perspectives, how changes in sea ice and other environmental parameters may be affecting Arctic living resources and the indigenous cultures and practices that depend on those resources,
- to identify possible measures that can be taken to mitigate the impacts of realized and anticipated changes, and
- to develop a document that provides a compelling blueprint for action for legislators, conservationists, Arctic residents, and others.

This final report contains the conclusions and recommendations of the workshop, a summary of the discussions held by break-out groups during the workshop, and papers describing various aspects of environmental change in the Arctic. In addition to the final report, the participants hope that the spirit of curiosity and cooperation that developed at the workshop carries over in the work that will be done to address the impacts of environmental change the Arctic.

The Context

There are many challenges to the future of Arctic communities. Climate change is one of these, but other aspects of environmental change are also of great concern to residents of northern Alaska. While the actual and potential impacts of climate change to the environment and to people are important and worthy of a great deal of attention and effort, they must be considered in the context of other outside influences on the people,



Map of the region on which the workshop focused.

communities, and cultures of the region. Environmental contaminants, industrial activity, overfishing, and other factors interfere or threaten to interfere with traditional patterns of resource use and the position of Alaska Natives within their ecosystems. Residents of these communities need to consider all aspects of their future as they determine what to do and how to set their priorities. As we identify ways to respond to the threats and challenges posed by climate change, we must remember the cultural and environmental settings in which those responses will be made, and make sure that Alaska Natives have the necessary information and ability to make the crucial decisions that will determine their futures.

In scientific circles, too, our workshop does not stand alone. There is a great deal of activity concerning environmental change and global warming. The workshop described here was designed specifically to look at ways that residents of coastal villages and researchers can work together to document the changes that are occurring, assess the likely magnitude of their impacts, and identify specific actions that can be taken in response. Our workshop should be seen in the context of the many workshops that have been held or are planned, the great range of research that has been and is being done, and the many large programs that have been created to look at various aspects of climate change and its impacts. We cannot attempt a complete list of all these activities, but note here a few that are particularly relevant to or active in the Alaskan Arctic. Some recent publications are listed in the Bibliography.

The Bering Sea Impact Study

The Bering Sea Impact Study (BESIS) is an activity of the International Arctic Science Committee (IASC). Its goal is to assess the effects of global change on the physical and biological environment of the Bering Sea region, and its cultural and economic impacts. The approach used is to construct impact scenarios based on computer models, including regional climate models, and on information and data on past impacts and their causes. The focus is primarily on the impacts of global change on:

1. Commercial, recreational and subsistence fisheries.
2. Marine ecosystems, particularly marine mammal and bird populations.
3. Resource-dependent communities, particularly with respect to subsistence hunting and fishing.
4. Terrestrial and fresh water ecosystems.
5. Non-renewable resource development and their transportation.
6. Public and private infrastructure: buildings, roads, airports and sea-ports.

Several workshop reports have been published and the study is now part of the nationwide assessment of climate impacts in different regions of the United States. The Alaska assessment is coordinated by the Center for Global Change and Arctic System Research at the University of Alaska Fairbanks.

The Alaska Native Science Commission

The Alaska Native Science Commission was created to bring together research and science in partnership with the Alaska Native community. Among its goals are the greater involvement of Native communities in research, and more research directed to the concerns of Alaska Natives. To address concerns about environmental contaminants and global change, the Commission is conducting a study to record traditional knowledge about these topics throughout the state, to consider the implications of this knowledge, and to promote a synthesis between traditional and scientific knowledge.

Arctic System Science

The National Science Foundation's Arctic System Science (ARCSS) Program supports research that increases understanding of the impact of the climate on every aspect of the environment, including social systems. ARCSS emphasizes research that looks at the complex environmental feedback mechanisms driven by climate change and attempts to incorporate a predictive capability for examining the possible impacts of future changes.

Researchers have found that complex interactions of tundra ecology, soil, hydrology and climate have the potential to increase emission of greenhouse gases, particularly carbon dioxide, from a warming Alaskan North Slope. The positive feedback of increased gases in a warmer Arctic has the potential to accelerate the current warming. Researchers have also used submarines, satellites, airplanes, ships, and ice camps to determine that both the thickness and extent of sea ice has diminished in the past decade. They are currently making improvements in computer models to incorporate new discoveries about the physical processes capable of driving variations in sea ice so that the impact of global warming on sea ice permanence may be predicted. ARCSS has initiated a new long-term project to examine the role of physical and natural processes that have/could affect social systems in the Arctic. The full suite of projects is not known at this time but will include projects that address potential impacts of global change on subsistence resources and social change for Arctic residents. ARCSS has also initiated a project that will provide information on the fate of carbon that provides the building block for marine productivity on the Arctic continental shelves. Again, the new project will examine future impacts of global climate change on sources of food for fisheries and marine mammals in Arctic waters.

The Arctic Research Initiative
NOAA's Arctic Research Initiative (ARI) began in 1997 with an initial emphasis on contaminant influences on western Arctic ecosystems and on Arctic haze, ozone depletion and UV flux. In 1998-1999, additional emphasis was placed on the Bering Sea Green Belt and on atmosphere-ice-ocean processes. In FY2000 emphasis shifted to research on climate variability and change in the Arctic. In addition, the NOAA ARI has become a source of support for U.S. involvement in work of the Arctic Council, especially the Arctic Monitoring and Assessment Program and the Arctic Climate Impact Assessment. Future work is likely to continue to deal with climate, contaminants, and marine ecosystem productivity.

Arctic Climate Impact Assessment
The consequences and impacts of climate change in the Arctic are likely to be substantial. An international effort called the Arctic Climate Impact Assessment (ACIA) has been initiated to address them. The expected impacts include changes in the physical environment, effects on biota, ecosystems, wildlife, and biodiversity, and impacts on important economic and social sectors in the Arctic, including fisheries, agriculture and forestry, infrastructure, human health, and indigenous people. Operating under the auspices of the Arctic Council, ACIA's work is guided by an Assessment Steering Committee that includes representatives of the Arctic Monitoring and Assessment Program (AMAP), the Program for the Conservation of Arctic Flora and Fauna (CAFF), the International Arctic Science Committee (IASC), and others. The lead country for this effort is the United States and an ACIA

Secretariat to coordinate the impact assessments has been established at the International Arctic Research Center at the University of Alaska Fairbanks.

The Southeast Bering Sea Carrying Capacity Program

The past three decades have seen tremendous environmental change in the southeastern Bering Sea, including the regime shift of the late 1970s and changes in populations of fish, birds, and mammals. To try to understand the relationship between changing environmental factors and pelagic ecosystem functioning, the Southeast Bering Sea Carrying Capacity Program (SEBSCC) was initiated in 1996. Funded by the National Oceanic and Atmospheric Administration's Coastal Oceans Program and jointly managed by the University of Alaska Fairbanks and the Alaska Fisheries Science Center and the Pacific Marine Environmental Laboratory of the National Marine Fisheries Service, the program began with extensive retrospective, monitoring, process, and modeling studies that have provided an intensive look at the southeastern Bering Sea shelf during a period of major environmental and ecosystem change, including shifts in sea ice cover and ocean temperature. In its third and final phase, the program will develop and test annual indices of pre-recruit (age-0 and age-1) pollock abundance that will support management of pollock stocks and help determine food availability to other species.

As the Conclusions and Recommendations below make clear, communication and trust are essential for true partnerships between the Native and scientific communities. While those communities are sometimes overlapping, there are nonetheless distinct differences in the ways they view the natural world and the role of people and in the ways they approach research. Our workshop was unique in its effort to place equal emphasis on both perspectives. Other initiatives have recognized the importance of doing so, and we hope that ours will be only the first of a series of efforts to build real partnerships to address the impacts of environmental change in the Arctic.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and Observations

Climate change is often seen by the general public as a rather vague possibility rather than as something concrete that is already changing peoples' lives. In Arctic Alaska, however, there are many indications of significant change over time. While variability is a characteristic of the Arctic environment, the observed changes tend to move in the same direction, indicating trends rather than normal fluctuation. Sea ice typically covers less of the Bering Sea in winter now than in the recent past. Permafrost is warming and in some areas is actually melting. Coastal erosion has become severe in many places. Such changes are not merely curiosities from a remote area. They have severe impacts on the lives of residents of northern Alaska, most of whom are Alaska Natives pursuing traditional ways of life deeply rooted in the local environment. The changes seen in the Arctic are also the early signs of changes in climate that are likely to affect much of the world in the next several decades. While some popular reporting may make global warming seem overhyped, changes are occurring. The impacts to Arctic residents and the lessons those impacts have for the rest of the country and the world are ignored at our peril.

With this in mind, the workshop participants noted that it is difficult or impossible to make accurate predictions about the way in which climate will change and the impacts those changes will have. A range of scenarios can be simulated through computer models, but specific changes in local conditions, much less the interaction between those changes, cannot be foretold. Instead, continued monitoring can assess the degree to which overall predictions match observed changes. Examining potential impacts of various changes can indicate to coastal communities and others the range of possible impacts they may face. While uncertainties will persist, it is clear that more attention is needed to assess the risks that we face and to identify actions that can be taken to minimize those risks.

In considering what is known today and what needs to be done, workshop participants made a number of observations on the state of our knowledge and its applicability to the responses that might be made to the impacts of climate change:

- There are significant disconnects among scientific disciplines. For example, there is little integration of the studies of lower trophic levels (e.g., plankton, invertebrates, etc.) in the marine environment with the higher trophic levels (fish, mammals, birds) that are used by people along the coast. More attention is needed to the species that affect people directly.
- Policy makers give too little attention to environmental change. Those who want to ignore climate change are able to block serious consideration by pointing to the economic costs of changing our habits. But, the costs of ignoring climate change are also real, and those who will pay for the disruptions it causes—such as the insurance industry, consumers, and government relief agencies—should be mobilized to support preventive action.

- Sea ice is particularly important in many respects, from maintaining healthy marine mammal populations to limiting the scope of industrial activity in the Arctic. We do not know enough, however, about specific regional scenarios for changes in sea ice extent and seasonality. To make plans, we need to have more detailed scenarios that can show specific changes in small areas to identify the potential impacts to communities.
- Alaska Natives have a great deal of expertise in observing the environment, extending back many decades in personal memory and farther in what has been handed down from past generations. Making systematic use of those observations and that expertise requires dedicated research and can provide a wealth of useful information. This knowledge can also be the basis for local observation networks.
- Subsistence hunting, fishing, and gathering are vital activities for Alaska Native communities, but it is difficult or impossible to express their significance. Attempting to place dollar values on subsistence activities and products implies that they can be replaced by cash payments, whereas subsistence as the basis for Native cultures cannot be replaced.

A common thread to these and other discussions during the workshop was that climate change is a far-reaching threat to coastal communities. Our conclusions are necessarily selective rather than comprehensive. Nonetheless, it is clear that we must give a great deal more attention to the impacts of climate change to communities in northern Alaska.

As noted in the previous section on Context, there are a number of initiatives addressing various aspects of climate change in the Arctic. As we act on the recommendations below, we should keep those potential partners in mind. Much research can be done within existing programs, without having to create new programs to address the specific ideas presented here. Many organizations active in rural Alaska, such as co-management bodies, have the capacity for participating in such research, reducing the need for recruitment and training of local researchers and observers. In other words, we can build on what exists rather than starting from scratch.

In considering how to carry out the recommendations below, workshop participants had a number of observations on the process of research:

- Collaborative research between communities' members and outside scientists requires continuity and time to build trust, train personnel, and learn to understand the perspectives and expectations of the various partners. This in turn requires funding commitments that allow for the development of long-term projects. Conversely, we must be careful in forming partnerships with programs that may end soon.
- Community-based programs should be coordinated or integrated so that the communities can make best advantage of the programs in which they participate. A local natural resource program is one way to keep track of the various initiatives and projects in which the community is involved.
- We need to involve young people, especially through schools. Collaborative projects that apply the science lessons to local experiences can help spark the curiosity of students, perhaps inspiring them to pursue careers in natural resource research and

management. A strong grounding in the basics of research and science will also help tomorrow's leaders make better informed decisions for their communities.
- Progress requires dedicated individuals, not just good ideas. For the recommendations to work, someone must respond to them and work to carry them out. For collaborative research, this includes both scientists and community members.
- Research involving the participation of local researchers often fails to recognize competing demands for the time of local participants, and thus fails to compensate them adequately or at all. While communities need to pay attention to issues of climate change, they also need reasons for taking part in collaborative programs.
- Using scenarios for future planning often involves "best-case" and "worst-case" predictions, which make statements about the future of real communities. No one likes to imagine bad things happening to one's home and loved ones, and so we must be sensitive to the stress caused by predictions of disaster to a village or a region.

Recommendations

Stemming from the conclusions and from the full range of discussions at the workshop, participants listed a number of recommendations in several categories. In addition, two overarching recommendations emerged:

- *Promote long-term commitments*. It may take several years for programs to develop and produce results, especially when those programs need to establish working partnerships between researchers and Native communities. Without long-term commitments, it may be difficult to justify the costs of training and to recruit local researchers.
- *Take better advantage of existing programs*. Research on climate change and research involving residents of coastal communities do not take place in a vacuum. There are a number of programs on which community-based research can build. These include the variety of studies noted in the previous section, and a number of community monitoring programs, such as those established through co-management groups.

<u>Research</u>
Much of the discussion revolved around the need for more data and the ways in which Arctic residents can become more involved in research.

- *Develop a formal plan for recording systematic observations by residents of coastal communities*. Coastal communities can add a great deal to current monitoring efforts regarding environmental change. A team of scientists and local observers should determine which measurements are appropriate for gathering by local observers and which factors are significant from the local perspective. Measurements might include such parameters as snow depth at specific locations and times, the dates of snow cover and snow melt, ice thickness at specific locations and times, data on body condition of harvested animals, the dates of arrival and departure of migratory bird species, and others. A system for recording these observations requires adequate funding for local participants, including proper training. The plan should provide opportunities for cooperative analysis so that local researchers can add their expertise. Community participation could be achieved in cooperation with organizations active in various aspects of environmental monitoring, such as the Alaska Eskimo Whaling Commission, the Alaska Beluga Whale Committee, and the Eskimo Walrus Commission.

- *Develop a system for reporting other noteworthy events*. In addition to observations of regular phenomena, unusual events are worth recording and analyzing. These include strandings or die-offs of marine mammals, birds, and fish; physical abnormalities in harvested animals; and unusual sightings of birds, mammals, fish, and insects. The reporting system for such events could be linked to the observation network, but the analysis of unusual events is likely to require additional expertise. A group of experts should be identified who can be called on when needed to help analyze specimens or observations to help determine what happened and what implications it may have for human and environmental health.
- *Promote the creation of better baselines of data*. Related to the previous two recommendations, existing baseline data are often from too few monitoring sites or over timelines that are too short. For the future, better monitoring systems should be set up to complement those involving Native communities. Effective monitoring requires archiving of data as well as ready access to those data for analyses and comparisons.
- *Document Native observations of environmental change*. As part of extending baselines, we need to draw on the knowledge of elders and other community members with extensive experience of their local environment. This work is particularly urgent, because when elders pass on they take a tremendous amount of information with them. The systematic documentation of Native knowledge can help identify patterns in the environment over time, helping sort out short- and long-term changes. In addition to documenting Native knowledge, people who are particularly knowledgeable about certain topics can be identified as resources to assist in further research.
- *Develop more detailed local scenarios for assessing the potential impacts of climate change*. Current models that predict the effects on the Arctic of warmer climates give general trends for sea ice and other parameters, but do not provide details for specific areas. Without such details, it is difficult to determine the range of changes and their likely impacts for Arctic communities. While firm predictions are beyond our reach, more details about the range of likely effects would help generate more plausible scenarios from which responses could be planned.
- *Make more use of integrative tools for analyzing data*. The data that are gathered are often not used as much as they could be. In part this is a question of data access, but it is also a matter of having tools, such as geographic information systems (GIS), that allow researchers to integrate various data sets to prepare complex analyses.
- *Allow time for the creation of real partnerships between communities and researchers*. Many funding opportunities and requests for proposals allow only a short time to respond. When those opportunities also request partnerships with communities, they often lead to hurried attempts to find Native partners and develop collaborative projects. Where possible, time and perhaps funding for the development

of real partnerships should be given. Partnerships can be made formal through the use of memorada of agreement (MOAs) and other such mechanisms.

- *Explore ways to make use of climate change*. Predictions of climate change indicate a number of effects, including more frequent severe weather and changes in ocean currents and other phenomena. Some of these may provide opportunities for alternative energy or for new patterns of resource use.

Policy

The policy implications of the workshop's conclusions were not discussed in great detail. Nonetheless, certain matters remained near the center of attention. These recommendations are thus general, but offer some insight into the thinking that lies behind the other recommendations. For thinking about the impacts of climate change, workshop participants outlined a useful series of questions:

- What do we know?
- What do we need to find out?
- What can we do or change?
- How can we prepare?
- How do we communicate with others how they will be affected and what they can do?
- How do we pay for it all?

- *Address the causes of climate change*. Human actions and the production of greenhouse gases have been identified as major contributors to climate change. Nonetheless, most research tends to examine the effects of climate change rather than tackling the more difficult question of how to control its causes. From a policy perspective, we need a greater willingness to examine the range of human actions that affect climate change and to develop means of changing our actions to minimize their impacts.
- *Recognize actual and potential problems*. Uncertainty about the reality of climate change can no longer be used as an excuse to postpone our response to its effects. Real effects are being seen in the Arctic, and a range of potential problems has been identified. Ignoring these warning signs will only lead to far greater costs in the future, when problems become crises.
- *Provide intrinsic valuations for natural resources*. The subsistence cultures of Arctic peoples and the resources on which they depend cannot be replaced. When considering the damage that climate change might cause, however, dollar figures are the usual way of estimating the effectiveness and necessity of various responses. Other means of valuing natural resources should be developed so that activities such as subsistence that are largely outside the cash economy are properly reflected in damage calculations.
- *Assess institutional cultures that prevent meaningful change*. One of the chief obstacles to effective response is the inertia of established institutions, from industries to government agencies. Understanding the nature of those institutional cultures is essential to identifying ways to bring about effective and timely responses to threats such as those posed by climate change.

Communication

Although Alaska Native communities are among the first to be affected by the impacts of climate change, they are not as involved in these matters as they can and should be. Often, this is a matter of communication, especially during and after projects. In addition to reporting results, researchers should remember to thank communities for their support.

- *Develop better ways to communicate results to Native communities*. Research that has involved Native communities or that has a bearing on community interests is of great interest to people in those communities. Nonetheless, research results are often not provided to the community in appropriate ways. Good communication should take into account Native ways of thinking and communicating, for example through visual and oral media rather than only in writing.
- *Provide training in communication*. Effective communication, especially in cross-cultural settings, is not a simple matter. Researchers can learn from one another and from community members which methods work best and how to convey results and the scientific principles that support them. Communication should stimulate curiosity and convey the excitement of science, which will help attract greater interest among community members, especially young people.
- *Consider a variety of means for communicating*. Local radio programs, regional newspapers, public lectures, mailings to community residents, and posters are among the many ways that can be used to announce projects, provide progress reports, and give final reports to communities and regions. Using generalists who have special skills in explaining science is another avenue, especially for large programs.
- *Teach scientists, agency personnel, and others about Native cultures*. For outsiders, Native cultures and ways can at times be confusing. Being sensitive to differences and to particular ways of talking and thinking is essential to working well in community settings. Written materials and in-person orientation sessions are among the ways that newcomers can be introduced to the ways of a community.
- *Teach community members about science and scientists*. Scientists, too, have particular ways of looking at the world. Research partnerships depend on community members' understanding of the principles and practices of science, which may vary among disciplines. In addition to introducing community members to scientists, such training should include an introduction to scientific methods and theories.
- *Review web-based programs to develop new ideas*. Many school districts in northern Alaska use the internet and world wide web to participate in research such as satellite tracking of wildlife. The web can be used for data management and access, and for frequent communication between researchers within and outside the community. We can learn a great deal from the experiences of schools and other organizations to develop effective ways of stimulating interest and participation in research and monitoring.
- *Promote professional recognition for the importance of communicating*. Many researchers would like to spend time reporting results to communities, but there are often too many competing professional obligations and pressures. Giving professional recognition to efforts to give results back to communities, for example by including

such efforts in tenure review for university professors, would help encourage greater effort in communicating effectively and often.

Education

Over the long term, education is the most effective means of improving our ability to understand and address our relationship with the environment and the consequences of environmental change. General curricula can be used nationally or worldwide to teach the basic principles, and local components can help show students how those principles apply to them and their regions.

- *Develop general curricula on climate change and our connection to the environment*. Public understanding of the potential impacts of climate change requires an understanding of what is involved in climate change as well as how humans depend on the environment for food, water, materials, transportation, and other aspects of our daily lives. Curriculum materials that can help explain and demonstrate both will create a better-informed citizenry.
- *Develop specific curriculum materials to show the local context of climate change*. Generalizations about climate change should be supplemented with specific local information to help students see how climate change may affect them and their home regions. These materials should draw on local customs, for example through involving elders in school programs. They should also include hands-on opportunities wherever possible, for example through taking weather measurements and recording observations. Science camps can make use of these ideas as well.
- *Promote interactions among schoolchildren from different places*. Sharing local experiences and observations with students from other parts of the country or world can help students learn more about others and more about the different ways that climate change affects various parts of the globe.
- *Make use of existing programs that involve students and teachers in research*. The National Science Foundation and other agencies have programs designed to give schoolteachers and students exposure to science through watching and participating in research. Such programs can help with education as well as communication, helping researchers become more involved in the communities in which they work.

DISCUSSION GROUP SUMMARIES

During the workshop, parallel discussion groups considered the physical effects and impacts and the biological effects and impacts of changes to sea ice and other environmental parameters in the Arctic. Not surprisingly, given the close connections between the topics, the content of the two discussions overlapped considerably. The discussions took place over a day and a half, and a complete record of what was said is beyond the scope of this report. A brief summary of each session, however, may illustrate the approaches taken in the discussions and the main themes that emerged. In addition to general discussions, each group examined a particular aspect of sea ice change in some detail.

Physical Effects and Impacts Group

Climate change is predicted to have many effects on the physical environment in the Arctic. The group began by reviewing some of the changes that are already being seen and that may be indicators of significant directional trends. Among the examples given were the following:

- Sea ice patterns in the Bering and Chukchi Seas have changed over the last 50 years. Multi-year floes used to be blown south in fall, reaching the shore near Barrow and passing through the Bering Strait to St. Lawrence Island. Today, these floes appear in November or December, after sea ice has already formed locally.
- Overall, freeze-up is later, so that fall hunting cannot begin until December or even January, instead of in November.
- In spring, the ice goes out sooner, and whaling crews have had to adjust their usual patterns to prepare earlier, go farther out, and be ready to return to shore sooner. In Barrow, the sea ice now goes out before July 4, and sometimes has left in June.
- In the western Canadian Arctic, sea ice today is only three or four feet (.9-1.2m) thick, whereas it used to be seven or eight feet (2.1-2.4m) thick. There is more snow in fall, which interferes with ice formation. The ice on rivers, too, is only about three feet (.9m) instead of the six to seven feet (1.8-2.1m) it used to be.
- The shore ice at Nome has broken up early the past few years, in part due to less snow.
- Sandy beaches have eroded and are now rocky. This corresponds with studies of the sea floor that have found sand where there used to be only gravel.
- Beaver are moving northward, and are now found in the Kotzebue area where they never were seen before.
- Sea ice cover in the Bering Sea corresponds well with the North Pacific Index, showing a general downward trend over the past three decades.
- The tundra has warmed and is now a producer of carbon dioxide, whereas it used to be a carbon sink.
- Sea level is rising, and will continue to do so for another 200 years due to melting glaciers and thermal expansion of the ocean water that is already there.

- Puffins are able to nest on Cooper Island near Barrow. Previously, only guillemots were able to nest during the brief snow-free period, but that period has gotten longer.
- The flow of ocean water north through the Bering Strait has been declining since the 1940s, and corresponds reasonably well with observed changes in the North Pacific Index.
- Permafrost is warming, and the active layer is getting deeper. This can affect the landscape as well as human structures such as buildings on pilings, roads, ice cellars, pipelines, runways, and so on.

This list was used as a starting point for identifying the kinds of changes that have been observed and that are expected in the near future. As a more systematic analysis of the impacts of climate change, the group listed the first-order effects of a warming climate in the Alaskan Arctic, noting some of things that will be affected. Many of the effects are the result of several of the first order effects, and the list is intended to be illustrative rather than exhaustive:

Reduced sea ice will affect the topography, quality, and composition of the sea floor in the areas that are no longer covered at least seasonally by ice. Storm surges, wind, and temperature will be affected by the increased amount of open water, especially in fall and winter. Primary production will be affected, as will the migration, distribution, and demography of marine mammals and other hunted species. Hunting safety will be affected by poorer quality ice and the ability of storms to stir up the greater expanses of open water. Industrial activity, such as shipping and oil and gas development, will likely increase as the obstacle of ice decreases.

Rising sea levels will increase flooding, especially in low-lying areas, harming human habitation as well as the habitat of many animals. Salt will intrude farther into wetlands and river deltas, affecting vegetation, fish, birds, and other species. Greater erosion and turbidity will affect settlements, hunting, and marine, estuarine, and fresh water productivity.

Melting permafrost will lead to structural damage in buildings, roads, pipelines, runways, and other human-built items, as well as to changes in the landscape through subsidence, draining of tundra ponds, and so on. Water flow, vegetation, and accessibility for animals and hunters will change. Methane production will increase as the active layer, which thaws in summer, gets thicker.

Increased water flow from less permafrost and more precipitation will cause greater erosion and thus more turbidity in rivers and streams. The growing season will get longer. Moisture levels and the amount and timing of precipitation will change, though perhaps differently in different regions. The life cycles of fish, insects, birds, plants, and mammals will change as their habitats are affected.

More extreme weather events will bring storms and their consequences, and increase the unpredictability of weather in the region. Such events will cause more frequent severe damage, as extremes of precipitation cause flooding and great fluctuations in temperature threaten, for example, nesting birds. Greater variation from "normal" patterns also means that people and animals must be prepared to cope with a wider range of conditions, which can be costly in financial and biological terms.

Changes in prevailing weather regimes, such as the jet stream, El Niño/La Niña, the Aleutian Low, the Pacific Decadal Oscillation and the Arctic Oscillation, and air and water currents, will bring a variety of changes that are difficult to predict. The interactions among these and with other first-order effects are complex and may lead to major shifts in general patterns of weather and climate across the Arctic and even the Northern Hemisphere.

Changes in seasonal patterns will force people, animals, and plants to adjust the timing of their activities, such as migration and breeding. Certain sequences of events on which many species depend may be altered, and those species may suffer. Irregularities in seasonal patterns may cause widespread mortality, if for example birds migrate earlier but then encounter a severe cold snap.

Warmer surface air temperatures will increase plant growth as well as prolonging the growing season, but may increase physiological stress for species that are adapted to cold. Insects may increase, and may expand their ranges, as may other species.

Following this exercise, the group focused its efforts on examining in greater detail the potential consequences of the reduction in sea ice. The other first-order effects could be examined in the same way, but there was not time to do so at the workshop. The participants did not have the necessary expertise to determine all the likely effects of reduced sea ice cover or their severity, so the following summary, like the previous one, is intended only to illustrate the ways that one may think about the impacts of climate change.

If the extent of sea ice cover in the Alaskan Arctic is reduced, the repercussions are likely to be felt far and wide:

Marine mammals will be affected directly and indirectly. Their distribution will change based on where sea ice is to be found. Reproductive behavior and success may change if suitable ice conditions are not as common, especially for species such as ringed seals that require shorefast ice. Body condition of the animals will be affected by the availability of food. Walrus that haul out on ice in the summer, for example, have already suffered when the summer ice retreats far from the shallow waters where walrus feed. The walrus have to swim great distances to get to food, expending far more energy than is required when the ice remains close to the shallower waters. Indirectly, marine mammals are likely to be affected by changes in the extent of industrial activity, such as increased shipping, oil and gas development, port facilities, pollution, and so on, as described below.

Fish and benthic organisms will be changed as the productivity of the water column changes. With less sea ice, some species will suffer and others will prosper. For benthic communities in particular, less sea ice may mean less ice gouging of the sea floor and more wind-driven turbulence. Increased industrial activity may bring another form of disturbance to many areas and may affect the distribution and migration of fishes, especially along the coast.

Shipping will increase as sea ice retreats, because ice is the primary obstacle to shipping in the Arctic. As access becomes easier, more development will occur, requiring more ship traffic to bring in supplies and take out ore, coal, or other products. Shipping through the Arctic, for example via the Northern Sea Route, is also likely to increase if ice is no longer a factor. This would bring in many more vessels traveling from the Pacific Rim to Europe.

Mineral development, including ores and fossil fuels, will increase as access to the Arctic becomes easier. This is especially true of offshore areas, which are primarily limited by the difficulty of operating in ice-covered waters. While sea ice is likely to continue to form in the winter in northern Alaska, thinner ice and a shorter ice season will make development more attractive, meaning more ship and aircraft traffic, more seismic testing, more construction, and more off-shore drilling platforms, all of which contribute to a noisier environment. On-shore deposits will also become more attractive, as the costs of extracting and exporting the products go down. More development will mean more pollution, more human activity, and the greater likelihood of an accident such as an oil spill. All of these factors will affect marine mammals, fish, birds, and the people who use them.

Port facilities will become more common as access improves and more resources are developed. Existing port facilities, such as the one for Red Dog Mine in northwestern Alaska or the docks at Prudhoe Bay, are already having an impact on the local marine environment. More facilities, or expansions of existing ones, are likely to have greater impacts to the local environment. They may also affect migratory patterns, and thus have regional impacts to wildlife and to humans.

Human communities will be affected in a number of ways. Greater industrial activity may mean more opportunities for work. As living marine resources and their accessibility are affected, locally produced foods may be replaced by store-bought foods, which are typically associated with a variety of health problems. On the other hand, increased contaminant burdens in wildlife may make local foods less attractive.

Mitigation efforts will be required to address many aspects of the disturbances caused by the loss of sea ice. Local response teams will be needed in case of accidents or spills, facilities will need to be designed to minimize their individual and cumulative impacts on the environment, and communities will have to respond to changes in subsistence production. It will not be possible to avoid or mitigate all the impacts of a reduction in sea ice cover, but it is essential to try to understand what will be affected and plan accordingly so that disruptions can be addressed before they cause widespread problems.

Biological Effects and Impacts Group

Coastal communities are concerned with climate change because, among other reasons, it will affect the animals on which they depend. Over millennia, indigenous peoples of the Arctic have seen and adjusted to many changes in environmental conditions. Recent experience and the predictions of climate models, however, suggest that the changes we see today are not part of the normal variability of an extreme climate, but are a directional movement towards a warmer climate with less sea ice in western and northern Alaska. With this in mind, the group discussed the potential effects that such changes would have for coastal communities and the species they use.

As examples of the types of changes being seen today, the group listed observations by various participants. As the list was developed, it became apparent that the observations actually fit in several categories:

Changes in Timing
- Gulls have been seen in November in Norton Sound
- Oldsquaws have been seen in February in Norton Sound

Changes in Condition
- Caribou taken at Deering were skinny

Changes in abundance
- Bowhead and walrus harvests were high or at the quota level at St. Lawrence Island in 1999
- Fewer oldsquaws and sandpipers are seen at Gambell
- More sculpins and humpback whales are seen at Gambell
- More spectacled eider are seen at St. Lawrence Island
- Fish stocks are low on the Seward Peninsula
- More species of marine mammals are seen off Deering, including bowhead whales, narwhal, and dolphins, while there are fewer bearded seals
- More jellyfish are found now in the Bering Sea

Unusual sightings
- A minke whale was seen in Norton Sound
- Caribou are migrating through Deering
- Stranded dolphins have been seen at Kivalina, Gambell, and on the Seward Peninsula
- Dark-skinned sharks have been seen off Gambell and Deering
- Hairless seals and deformed seals have been taken by hunters

Other
- Sea level and lake levels have been rising at Gambell
- Shorefast ice melts rapidly now
- Old trees, over 400 years old, are being eroded away on the southern Seward Peninsula

- Walruses used to be harvested by Thanksgiving at Savoonga, but recently the ice has not solidified until late November or December, and now not until mid-December
- The spring harvest of walruses at Gambell used to occur from late May through June, but is now mostly in May.

Building on these discussions, the group used St. Lawrence Island as the focus of a more detailed assessment of what might happen as a result of climate change. The group noted, however, that we must be careful when we speculate about the potential impacts to coastal communities. Predictions are very difficult to make, and the residents of coastal communities may not wish to see their futures placed in hypothetical scenarios of climate change. Nonetheless, it is important to try to assess the real consequences of observed and predicted changes so that we can better prepare ourselves to respond.

For residents of St. Lawrence Island, walruses are a critical resource. If sea ice retreats so that the winter ice edge is near St. Lawrence Island rather than farther south in the Bering Sea, a number of things may happen to walruses and other marine mammals and to the communities that use them. Rather than trying to predict what will happen, the group made a number of observations about the relationships among people, marine mammals, and sea ice:

> Native peoples of the Arctic coast have depended for millennia on ice-associated marine mammals. On St. Lawrence Island, bowhead whales, walruses, bearded seals, ringed seals, spotted seals, ribbon seals, beluga whales, and polar bears are all important as economic, cultural, and spiritual resources. It is particularly difficult to convey the significance of these species and their use because they are so central to the culture and identity of those who use them.
>
> Reduction of sea ice and increasingly unpredictable weather conditions have changed the availability of marine mammals to hunters on St. Lawrence Island. The extent, seasonal timing, and characteristics of sea ice strongly influence the availability of walruses for harvests. Similarly, harvests depend on weather conditions suitable for boating and hunting.
>
> Sea ice cover and weather conditions also influence the population dynamics of ice-associated marine mammals. For example, traditional knowledge includes the observation that fresh snow cover insulates newborn walrus calves from sea ice. Scientific studies predict that declining ice cover will increase the amount of energy that walruses must expend while foraging, thereby decreasing productivity and calf survival.
>
> Changes in sea ice cover are predicted to be more pronounced in some parts of the range of Pacific walruses than other parts of their range. Thus, walrus hunting communities will be affected differently. Other marine mammals may move northward into the area, while ice-associated species may decrease in local abundance. Whether the new species will be attractive to hunters is not known.

Reduced ice cover is likely to change human activities in Arctic waters. Oil development, commercial fishing (including shellfishing and bottom trawling), and tourism are likely to increase in areas where the ice is reduced, with negative impacts on marine mammals. Increased shipping traffic is predicted to bring more chemical and noise pollution. If icebreaker traffic increases, it will directly affect the sea ice habitat of marine mammals and give some species such as walrus temporary access to areas from which they would otherwise be blocked by solid ice.

Reductions in ice cover have been associated with decreased primary productivity, which in turn is likely to lead to decreased biomass of the benthic filter feeders that walruses eat.

Directional changes in the patterns of walrus and other marine mammal use by residents of St. Lawrence Island and elsewhere will lead to changes in cultural patterns.

PERSPECTIVES ON ENVIRONMENTAL CHANGE IN THE ARCTIC

Six papers were commissioned to form a background report for the workshop, intended to help participants prepare by reviewing some of the available information concerning environmental changes in the Arctic in general and in the northern Bering and Chukchi Seas in particular. Three additional papers were prepared following the workshop to supplement those already written. Together, the papers present a variety of perspectives on environmental change, from the Native community and from several scientific disciplines.

Caleb Pungowiyi sets the stage with an outline of the Native observations and concerns that were the impetus for holding the workshop. George Noongwook addresses Yupik Eskimo knowledge and beliefs in regard to climate change. Igor Krupnik summarizes Native observations presented at the workshop and comments on the process of gathering traditional knowledge about environmental change. Gunter Weller describes the general trends of climate change across the Arctic, with specific observations from many areas including northern and western Alaska. Krupnik discusses the human presence in the region over time, and discusses today's patterns of habitation and resource use and the need for better understanding of human-environment relationships. Jackie Grebmeier and Ken Dunton review research and findings on the benthic environment in the northern Bering and Chukchi seas. Igor Melnikov reports his findings from many years of research on floating ice stations in the Arctic Basin. Alan Springer covers the processes of and dynamic relationships in the water column, from plankton to marine mammals. Lloyd Lowry writes about current knowledge of marine mammals and the implications of changes to sea ice.

NATIVE OBSERVATIONS OF CHANGE IN THE MARINE ENVIRONMENT OF THE BERING STRAIT REGION

Caleb Pungowiyi

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Since the late 1970s, Alaska Natives in communities along the coast of the northern Bering and Chukchi Seas have noticed substantial changes in the ocean and the animals that live there. While we are used to changes from year-to-year in weather, hunting conditions, ice patterns, and animal populations, the past two decades have seen clear trends in many environmental factors. If these trends continue, we can expect major, perhaps irreversible, impacts to our communities. With these concerns in mind, we believe this workshop will be a vital opportunity to discuss our concerns and observations with scientists who are working on similar issues in the same area, and to work together to figure out what can be done.

Beginning in the late 1970s, the patterns of wind, temperature, ice, and currents in the northern Bering and Chukchi Seas have changed. The winds are stronger, commonly 15-25 mph, and there are fewer calm days. The wind may shift in direction, but remains strong for long periods. In spring, the winds change the distribution of the sea ice and combine with warm temperatures to speed up the melting of ice and snow. When the ice melts or moves away early, many marine mammals go with it, taking them too far away to hunt. Near some villages (such as Savoonga, Diomede, and Shishmaref), depending on the geography of the coast, the wind may force the pack ice into shore, making it impossible to get boats to open water to go hunting or to move boats through if they are already out. The high winds also make it difficult to travel in boats for hunting (even winds of 10-12 mph from the wrong direction can create waves 2-3 feet high, stopping small boats), reducing the number of days that hunters can go out. For all these reasons, access to animals during the spring hunting period is lower now than it was before.

From mid-July to September, there has been more wind from the south, making for a wetter season. With less sea ice and more open water, fall storms have become more destructive to the coastline. Erosion has increased in many areas, including the locations of some villages, such as Shishmaref and Kivalina, threatening houses and perhaps the entire community. Wave action has changed some sandy beaches into rocky ones, as the sand washes away. There have been no new sandy beaches, but there are many new rocky ones.

The south shore of St. Lawrence Island has also been affected a great deal by erosion in recent years. Some shallow spits that used to be above water are now underwater, due perhaps to a combination of higher water and erosion. The storms and high waves—up to 30 feet—also change the sea bed near shore. After storms, kelp and other bottomdwelling plants and animals such as clams can be found washed up on the beach. These disturbances to the bottom affect shallow feeders such as eiders.

The formation of sea ice in fall has been late in many recent years, due largely to warmer winters, though winds play a role as well. In such years, the ice, when it does form, is thinner than usual, which contributes to early break-up in spring. Another aspect of late freeze-up is the way in which sea ice forms. Under normal conditions, the water is cold in fall, and permafrost under the water and near the shoreline helps create ice crystals on the sea floor. When they are large enough, these crystals float to the top, bringing with them sediments. The sediments have nutrients used by algae growing in the ice, thus stimulating the food chain in and near the ice. When the ice melts in spring, the sediments are released, providing nutrients in the melt water. In years with warm summers and late freeze-up, on the other hand, the water is warm and freezes first from the top as it is cooled by cold winds in late fall or early winter. Less ice is brought up from the bottom, and fewer nutrients are available in the ice and in the melt water the following spring, and overall productivity is lower.

Precipitation patterns have also changed. In the last two years, there has been little snow in fall and most of the winter, but substantial snowfall in late winter and early spring. In the winter of 1998-99, the weather was cold so that the ice was thick, but there was no snow. The lack of snow makes it difficult for polar bears and ringed seals to make dens for giving birth or, in the case of male polar bears, to seek protection from the weather. The lack of ringed seal dens may affect the numbers and condition of polar bears, which prey on ringed seals and often seek out the dens. Hungry polar bears may be more likely to approach villages and encounter people.

Other marine mammals have been affected to greater or lesser degrees by the changes in sea ice, wind, and temperature. The physical condition of walrus was generally poor in 1996-98, as the animals were skinny and their productivity was low. One cause was the reduced sea ice, which forced the walrus to swim farther between feeding areas in relatively shallow water and resting areas on the distant ice. This is the pattern for females and young in summer, and when the ice retreated far to the north in the Chukchi Sea, the animals suffered. Males typically haul out on land, and may have eaten most of the food near the haulouts, forcing them to go farther in search of clams. Due to wave action and sedimentation, the productivity of the sea bed may have declined, too, making it harder for walrus to find food. In the spring of 1999, however, the walrus were in good condition following a cold winter with good ice formation in the Bering Sea. When the winter ice forms late and is too thin, walrus cannot haul out and rest the way they need to, and they will be in poor condition the following spring.

Most seals seem to be doing fairly well. Hunters have been having more success hunting bearded seals lately. The seals are in good condition, and it may be that there are more of them or that they are concentrated in hunting areas for some reason. Spotted seals, on the other hand, seem to have declined from the late 1960s/early 1970s to the present. In 1996 and 1997, in which spring break-up came early, there were more strandings of baby ringed seals on the beach. These weanlings were probably left on their own too early. The mothers train their young on the shorefast ice where they den, but if the ice melts, the seals must abandon their dens early. Ringed seals seem to need more time to train their young, and are greatly affected if spring is early. There are fewer seals in the Nome area these days, perhaps as a result of less shore ice for ringed seal dens.

There are many other biological changes and effects in the region, such as:

- In spring, bird migrations are early. Geese and songbirds have been arriving in late April, earlier than ever before. Sudden cold snaps at this time of year can harm the birds. Snipe seem to be affected most, perhaps because they need unfrozen ground to feed, and many die in such cold spells.
- In August of 1996 and 1997, there were large die-offs of kittiwakes and murres, though other birds seem to be doing reasonably well.
- In the warm summers, especially if they are also dry, many different kinds of insects appear on the tundra. These include lots of caterpillars on bushes, and then butterflies. Other bugs that haven't been seen before have appeared, though mosquitoes are still the same.
- Chum salmon in Norton Sound crashed in the early 1990s, and have been down ever since.
- The treeline has moved westward across the Seward and Baldwin Peninsulas (*i.e.*, into formerly treeless areas). Bushes are getting bigger and taller. Willows are now like trees, taller than houses, whereas in the 1970s they were small and scrubby.
- Mild winters with little snow have been good for ptarmigan, which are healthy and abundant. This may also be a result of low hare populations, leaving little competition for the ptarmigan.

There is no record of this type of extended change. In the 1880s, during the time of the Great Famine in western Alaska, there were very cold winters for a long period. The main factor in the famine was the decimation of walrus and whale populations due to the commercial harvest by Yankee whalers, but lots of ice and the long, cold winters did not make things easier.

As we think about the future and where these trends may lead us, we wonder what alternatives are available to Native villages in Alaska and elsewhere in the Arctic. If marine mammal populations are no longer available or accessible to our communities, what can replace them? In the Great Famine, there were no alternatives to the food provided by hunting and fishing. Today, there are stores with food and other resources that can be harvested. A gradual change might give us time to adjust, but a sudden shift might catch us unprepared and cause great hardship. As managers, we need to think about the overall effects on marine mammals and other resources. Some may adjust, but others will not. The polar bear and walrus are likely to be the most affected. With these thoughts in mind, we need to consider the potential emergencies facing villages that depend so heavily on marine mammals. How can we prepare ourselves, and how much can be done to prevent hardship?

Our ancestors taught us that the Arctic environment is not constant, and that some years are harder than others. But they also taught us that hard years are followed by times of greater abundance and celebration. As we have found with other aspects of our culture's ancestral wisdom, modern changes, not of our doing, make us wonder when the good years will return.

NATIVE OBSERVATIONS OF LOCAL CLIMATE CHANGES AROUND ST. LAWRENCE ISLAND

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The most neglected portion of change which, I think, is indirectly caused by changes in our environment, is the belief system of the Yupiks (the people of St. Lawrence Island and some Chukotkan villages in the Russian Federation). These people truly believe that a "life in balance" encompasses spiritual (not of this world), physical (of this world) and environmental relationships in order to live a "long life." Lincoln Blassi, who was born in 1894, said:

> Living life with a "purpose," that there is a "plan" made by the "Ulimaghista" (O-lee-ma-ghis'-ta, "The Maker") that our purpose here on earth is to use the "gifts" from "The Maker" or "Apa" (Grandfather, which was not used loosely or in vain because He was considered "big and holy"). The Plan was already done, from what I have heard from our ancestors, the rules were already set and for those (people) who have obeyed the teachings and rules…will live a long and fruitful life. They would pray to ask for help and sympathy (from "The Maker") after observing the weather. If the weather is good for hunting, they'll pray at night, this was especially true for whaling. I am comparing this to what I have heard and learned when I was going up.

And then he went on to provide examples of not living life in balance with nature, all having to do with "non-obedience, disrespect to natural and spiritual belief systems or wrong-doings." Some examples were: changes in modes of transportation that contribute to noise and air pollution, sleep cycles changing, language usage, clothing, cash economy that he said are contributing to "imbalances" in nature. Therefore, these imbalances cause more frustration levels, depressive states because they are not able to go and hunt like they use to because of climate changes.

More observable climate change in wind patterns is becoming more frequent and intense around St. Lawrence Island. Herbert Kiyuklook, born 1901, said that back then "the weather was calmer, allowing us to go paddling, and ferrying our boats across ice to a greater distance." During the spring, the ice would become ideal: generally flat, fast (free of snow and bumps) and pressure ridges and that ice is named Sikughlluwhaq (se-kuwh'-lou-whak). During the winter, ice conditions allowed hunters to haul their catches over ice with ease and with great efficiency. The games and wildlife were readily available because of their close proximity to the village. There was an abundance of "qighuneq (kee-wuu'-nek) or northern young murres who become flightless because they become so fat and cannot go anywhere. These were the periods they concentrated in gathering as much as possible because they knew that there were going to be periods of scarcity . He went on to say that now it has become very different, more intense storms that last longer than they used to, which does not allow the concentrations of northern young murres to come.

Sea ice changes were also observed by the local people. Frank Oktokiyuk said that now:

> There does not seem to be any really heavy pack ice to speak of between the Chukotkan and St. Lawrence Island coasts. Ice would generally form and combined with persistent northeastern winds bring in ice-bergs from the polar ice caps all combining to form a solid mass of ice by November, enough so that it was safe to go out and do your ice hunting. [He also reiterated Kiyuklook's observation of concentrations of young northern murres.] The polar ice-bergs would even come as early as October.

But the winds now constantly changing from one direction to another and with more intensity contributes to the delays in the packing of ice and a late freeze-up occurs as it does now generally in December.

Oktokiyuk went on to say that the ideal is the north wind, the easterly currents (maaqneq) then begin to move, which becomes great for ice hunting, because the ice would move inshore depending on the time of day. The westerly currents (ikevreghaak), the ice would begin its off-shore motions, that was the time to head home. When a storm is brewing, the ice becomes very agitated because it is wind-driven then and no matter how thick or how big a pan the ice is, it begins to deteriorate very rapidly by the time the storm hits the coast. The ice begins to build huge pressure ridges along shore-fast ice or along the coast, going under or piling, ice pans moving in circular motion and eroding ice pans just like you are "winding a rope" when they hit shorefast ice or coastal lands. Then it becomes a very dangerous situation for hunters.

We call this phenomenon "Taglaghneq" (daw-law-nek) which is caused by the great force of wind driving the ice pack inshore at an alarming rate. Initial indicators are very thick, dark steam from freshly opened leads near shore in a very cold environment. These clouds or steams were called "puyughpak" (pu-youwh'-bak, "soot-like") from the appearance of thick dark steams arising. Another wind-driven phenomenon on the sea ice relative to "Taglaghneq" is "Pequneq" (ba-ko'-nak), a coning of thin or freshly formed ice pushed by the storms before it crashes down and producing a small open lead for a very brief moment that closes almost instantly. If you get caught in one of these, you will not have time to escape! We have lost some of our people in these conditions all in the name of seeking food for survival. Those who have experienced these phenomena, including Oktokiyuk, say that it is "the most frightening experience you can imagine." This is when all your survival/physical training is put to use, rules learned and time honored avenues to take to escape from danger.

Therefore, at this time and moment, there are more frequent windy/atmospheric conditions occurring that makes it nearly impossible to hunt because of these phenomena happening that contribute to undesirable conditions. "Sikughllugllak" (see-ko'-luuwh-luk), very bad rough, jagged ice conditions, make difficult, dangerous conditions to man impeding their hunting abilities leading to frustrated and depressive states. These conditions are the forces of too-fierce northerly winds that cause ice pressures near shore and even off-shore.

These constant northerly winds also indicate that the ice break up is going to be early and swiftly move away ice offshore because of the thinness of ice far offshore that becomes very unstable, therefore an early break-up occurs, coupled with the climate warming trend. It makes hunting less frequent and dangerous because you always have to “chase the ice” where much needed marine mammals are. It can become expensive in terms of more fuel/gasoline usage and less likely to be successful because even 10-15 knot winds can produce wave action in vast open water conditions and then you have to head home without being really successful, as is the case more often because of unstable weather conditions.

In contrast, Oktokiyuk and others reiterated, shifting winds will impede the progress of the ice systems to move and will allow very ideal weather/ice conditions for ice edge marine mammals to be in close proximity near shore and that allows the hunters to be very successful in stalking, killing, and retrieving of marine mammals. But then again, those conditions are becoming infrequent because of more extreme weather. It may be another cyclic actions of arctic systems, but the last 10-20 years we are seeing more of the extreme than we are seeing of the ideal.

This frequency of more windy and warm conditions also produces other “kinds” of ice to form: “Ugmetaghiq” (uw-met’-ta-ghek) thin ice, “qanigvik”(ka-nik-vik) snow covered small open leads, “qagitek”(ka-gi-tick), “qenghuk”(ken-woke) very rough ice caused by either wave action or granulating of ice due to ice pressure actions. Some of these can be dangerous like the camouflaged snow covered leads generally due to warming of climate and some just plain impede efficiency because of the abrasive conditions of the ice formed by wave-action or granular ice. It also forces the marine mammals to move offshore where there is a chance of more open leads where it is in constant motion due to water currents, and that allows them to surface more frequently to breathe the much needed oxygen.

Jimmy Toolie, born 1903, states that “the observation of the sun, moon, and stars are being impeded by more persistent cloud cover.” The celestial stars, sun, and moon were observed and studied since time immemorial because they were excellent indicators of weather forecasting, and when coupled with observations of ocean currents and ice behavior would allow these “expert observers” (those who learned to read the stars, moon, and sun) to predict the weather accurately and consistently. There was a man named “Suluk”(Sue-look) from Southwest Cape of St. Lawrence Island who was sought for advice because of his expertise in reading the weather patterns and was accurate in weather forecasting based on his experience of vigilant observations of stars, atmosphere and the environment of Gambell. Toolie recalled that every morning the “Tungtut” cluster of stars shaped like a caribou or “the Big Dipper” were observed (when clocks were not available) and at a certain position it would be the time to get ready for hunting because it would be daylight soon. Therefore, we do need local weather forecasting capabilities to warn us of weather and with the help of modern technology and information from the National Weather Service, we can achieve that. An example is the Automated Weather Observations Systems that are currently used by the aviation companies.

The problem of coastal erosion around the coast of St. Lawrence Island has become more pronounced within the last 15-20 years. My brothers-in-law had to move their camp cabin towards inland because the coastline there had severely eroded to a point where their cabin was becoming closer and closer to the beach. And finally, in 1985, they decided to move their cabin. In the Village of Gambell, the beach in front of the local airstrip had to be “sea-walled” because of severe wind-driven waves displacing gravel on to the airstrip especially during the October storms. The ancient village site in Siquvek is under water because of coastal erosion. I remember seeing the old meat caches still intact in the early 1960s but most of them are under water now.

Water level has risen within the last 20-30 years. A shallow point in front of the local school here in Savoonga no longer appears during low tides like it used to back in the 1960s and 1970s. I can remember as a kid that we used to go out to the point during low tides and collect baby sculpins or “kayengenghaaq” from under the rocks. During extreme low tides we could even walk out farther. I have seen other areas where this has happened, it does not really have any thing to do with erosion but maybe water levels have risen, nevertheless this contributes to coastal erosion during storms. Our beach below the village had quite a bit of sand, enough so that we would leave out boats without having to worry about waves taking them out, but now we cannot because the sand has been displaced by storm-driven wave action. A seal rookery at Sikneq Point on the southern coast of the island has gone under water. The rocks do not appear as they use to during low tides. The ringed seals and spotted seals would go on top of the rocks to rest. But that has not been the case currently and the only cause I can think of is the rising of the sea level. There are probably other areas with similar occurrences around our coast, all having to do with the water level rising.

In conclusion, climatic changes have occurred affecting sea ice, increased atmospheric activity (windier conditions), and coastal erosion. It is becoming increasingly difficult to conduct successful subsistence activities within our own hunting societies because of climate changes perhaps due to the warming trend as expressed by the scientific community. Then it is probably safe to say that changes are going to become a daily part of our lives, and the window of opportunity for conducting successful subsistence activities is going to become shorter because of the warming climate. It is then up to us to determine how, as hunters, we can be more efficient and safety minded in terms of retrieving and stalking marine mammals. In light of more unstable weather conditions, I think that it would help if we can anticipate these changes based on observations and data collected by the scientific community and also observations of local hunters, and make a collective prudent decision of where and when to concentrate our efforts in order to feed our souls’, physical, and biological needs.

We cannot change nature, our past, and other people for that matter, but we can control our own thoughts and actions and participate in global efforts to cope with these global climate changes. That I think is the most empowering thing we can do as individuals.

NATIVE PERSPECTIVES ON CLIMATE AND SEA-ICE CHANGES

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Introduction

This paper is a short overview of some ideas and statements expressed by several of the workshop participants who represented Alaska Native communities from the northern Bering Sea-Chukchi Sea region (see Participants List, this volume). By no means does it pretend to be a summary of the environmental knowledge shared by some 15 experienced hunters, resource managers, and community leaders from several villages. Even less does it represent a common "Native perspective" on Arctic climate and sea-ice change. Instead, this paper is intended, first and foremost, to let the voices of Native observers be fully heard through extended, direct quotations.

In reviewing Native statements on climate and ice change, academic scientists and the public at large have to consider the conditions under which these data have been documented and the format in which they are presented. First, beyond some general views (such as, "the ice and weather indeed are changing these days"), we are less likely to capture a uniform Native perspective from the residents of the area that extends from Barrow to Nunivak Island than we are to grasp a shared perception of Arctic climate change from the scientific community. As will be shown below, changes *do* occur and they are fairly substantial. Nevertheless, people experience changes *differently* along the northern and western Alaskan coastline.

Second, the section below is based upon several individual observations and comments offered by Native participants that were recorded and written down during the three-day workshop. In a condensed form, those statements are summarized in Appendix 1. In addition, a few extended interviews were specially recorded during the days of the workshop. However, unlike the edited (and highly polished) academic papers prepared in advance as a background report for the workshop, the Native contributions were merely spontaneous voices spoken and heard at the meeting. The statements below are transcripts of oral statements and comments given by people who more often than not are more comfortable on the moving Arctic ice than at a conference podium. We also have to keep in mind that many of the speakers use English as their second language and that they are far more accustomed to share their observations of the environment and its changes in their Native language and in a different social setting.

Third, thanks to George Noongwook's post-workshop contribution to this volume (Noongwook 2000), we already have an opportunity to grasp some valuable outcomes of the partnership forged at the symposium in Girdwood. Noongwook's paper is a highly eloquent representation of the ways local hunters perceive and discuss the changing ice and weather conditions that affect their lives and the well-being of their communities. At the same time, it is already a *written* product of reflections stimulated by discussions and mutual exchange of data and perspectives initiated by the Girdwood meeting. Therefore, it greatly expands the spectrum of potential formats of documentation of native knowledge, from personal observations to public statements, extended storytelling and interviews, and now written texts.

Whereas environmental observation is a life-long phenomenon in northern communities, speaking and writing about the environment and its changes is not. As this paper illustrates, we have a long way to go and much work to do before individual oral statements and personal observations can be transformed into systematic monitoring efforts and orderly documentation conducted in Native communities, by their members, and for their own sake. As such, we are at the very beginning of new tradition of *listening* to each other's ways of documenting the environment and of *reading* each other's patterns of analysis of change. The final section of this paper offers some general reflections on the status of knowledge shared by local hunters. It discusses both potential gains and obstacles concerning the ways in which this knowledge could complement and be complemented by data and approaches generated by the community of Arctic scientists.

Native Perspectives

1. Residents in many Northern communities clearly see changes in weather, ice, and marine biota that are taking place during their lifetime

"Climate change is becoming obvious to us. When we completed our land claims agreement [around 1984], we thought that protected areas and parks were going to be the best way to protect our land and its resources. Today, however, we see these conditions changing and our needs may change too.

"Past Aklavik, there is a place called Fish Hole. It has changed in many ways in recent time. That water just runs differently. Rocks fall into the Big Fish River. Dead fish are found on top of the ice."

Billy Day, Inuvik, Northwest Territories, Canada

"In 1996, when I was doing research on sea-birds on St. Lawrence Island for the Park Service, I talked to the elders of Gambell and Savoonga about their observations of change and how it was reflected in their lifetime. The main comment I got from the interviews is that people were seeing changes but these were not being documented properly.

"My aunt, Mabel Toolie, said [to me]: 'The Earth is faster now.' She was not meaning that the time is moving fast [these days] or that the events are going faster. But she was talking about how all this weather is changing. Back in the old days they could predict the weather by observing the stars, the sky, and other events. The old people think that back then they could predict the weather pattern for a few days in advance. Not anymore! And my aunt was saying that because the weather patterns are [changing] so fast now, those predictions can not be made anymore. The weather patterns are changing so quickly she could think the Earth is moving faster now."

Caleb Pungowiyi, Kotzebue, Alaska

"The changes are affecting our diet in Deering too. There used to be walrus, there should be walrus, we could see walrus all the time. And then they were gone. Now they are returning, slowly. We normally hunt ugrook [bearded seal] in the springtime, every family, every house in Deering. We do it every year when the ice break starts. We have 15 boats in our town and for every house we used to get maybe 5 or 6 ugrooks. Last year the ice come and go, and we brought maybe 5 ugrooks into our town. So, we are very short of seal-oil. We go for miles and miles in boats and we spend hundreds and hundreds gallons of gas. But there was nothing, just clean white ice: no ugrooks, no seals.

Those changes in our ocean, they are affecting us. The people in Deering, maybe not only in Deering but also in other communities along the coast too. Changes are coming and we have to learn how to live with them. They are coming anyway. We have to change, adapt, and this will be hard, it will be difficult."

Gibson Moto, Deering, Alaska

"The first sea ice that I noticed [i.e., that left a deep impression] was when going on a single-engine airplane. [It was] on my first trip to Nome, on April 25th, 1943. We flew from Gambell toward King Island. From the end of the Island to the north and northeast, right up to Nome, there was just solid ice all over. There were but a few breaks – not open leads but just lines across the ice in between the mainland and the island.

"This I believe, maybe at that time it was always like that, because back then we had more fair weather and cold weather. Today – as Caleb told us about his trip to Nome from the island when he looked down – it was all broken ice everywhere, all the way to Nome. And nowadays it is most often like that."

Conrad Oozeva, Gambell, Alaska

"We can see changes in our environment – I am from the northeastern Bering Sea-southern Seward Peninsula area. It's happening through my lifetime. In my area we [now] have timber coming down almost to the shoreline, all the way on the coast. These are full-grown timber, maybe 500 years old. They come up on the beach because of the heavy storms, beach erosion. We never saw them before but now these can be seen all along the coast.

"And another thing in my in area – the ice is not stable anymore, it is not too good in springtime. I don't know, maybe the water temperature is coming up. So, in the spring time when we go out hunting for seals in the day like this, sometimes it's a real warm day or they may even come in groups of two or three days. We can go out hunting to the shore ice and then we come back right to the beach in the boat. The shore ice is melting so fast – it's like opening your hot water socket, and the ice is melted away at once. Maybe the temperature is going up real fast. Before we could go out hunting, come and go – but never like that.

"I noticed that and we also talked about it at one of our elders' meetings. We just talked about all these changes. I do not know what's going on with our weather and what is going to happen. Because these changes may affect our ways of subsistence hunting, and also the fish stocks. It may impact the whole system."

Charles Saccheus, Elim, Alaska

2. Hunters' experience – whether called "Native knowledge," "local knowledge," or "traditional knowledge" – is a very powerful source of information; it is uniformly held in very high esteem by Native people

"We are talking here a lot using all this terminology and most of us are probably not aware of the scientific terminology. Although take people like Conrad [Oozeva] – he is a life-long observer, a living database. He is very articulate in his first language [Siberian Yupik]. He knows at least 30 different types of snow and ice conditions [see Appendix 2]. He is very well versed in knowledge about how the [ocean] currents are flowing and he knows how to get out when the ice is moving. He knows about the winds in the wintertime and about ice formations, and different weather patterns – he has his own equivalents for all these terms plus some 60 years of his personal knowledge.

"We have our Native versions of knowledge about all these wind and ice patterns, and it has been passed down through the generations. And people, like Conrad, they have lived with this knowledge all their life. I mean, they have knowledge on everything that pertains to the ecosystem, to the iceberg change, to the resources, and marine biology. I guess we have our own versions, in terms of understanding the comprehensiveness of our environment and all the necessary terminology. For every conceivable condition of snow and ice pattern, which is either annual or through generations. And we have stories of all these changes based upon comparative experiences and observations.

"We believe we have been put by the Creator in this ecosystem, to live on its resources, to be in sync with the ecosystem."

John Waghiyi, Savoonga, Alaska

3. Local observations are particularly detailed in identifying unusual indicators of change, such as extraordinary weather/ice conditions or rare game animals

"The other fall, last fall – we never used to see bowhead whales come by in Deering. And now they are there: two bowheads right in front of the village. We even wanted to go out and get a black whale. We never had a bowhead whale in Deering in my time. We also have reports of those long-nose dolphins washed out on the beach. When they were washed out one day, they were completely dead. But they are coming, they came again, like [during] past two or three years. You can see nine of them swimming by in front of the village. Those are dolphins, black-colored; we never had them before and now they are coming back."

Gibson Moto, Deering, Alaska

"It seems to be there are lots of minke whales in our area these days. This is the first time in my life – I've never seen a minke whale before. When I saw the first one in my life, a few years ago, I thought it was a killer whale. But they are different. We are seeing now a lot of minke whale in our area – it's pretty unusual.

"Another change I've noticed – I am a monitor for the Alaska Beluga Whale Committee – it was almost five years ago after a big storm. I went along the beach with my four-wheeler, and I came across something that I thought was a young beluga whale, maybe 12 feet long. It looked like a full-grown. When I looked at it, it was a dolphin. We never see dolphins in this part of the country. So, there must be some animals feeling different temperatures and they are coming in to our area."

Charles Saccheus, Elim, Alaska

4. Elders' and, generally, ancestors' experience is usually considered the ultimate reference in documenting changes

"My uncle did trapping from top of the Gambell Mountain and he used to go to check his traps every day. And I remember him saying sometimes that he is seeing now a different type of ice. He mentioned that the thick ice is now coming in."

Conrad Oozeva, Gambell, Alaska

"They [the animals] are coming back. The elders always say: the animals will return. But we were too young then, we did not believe them. The elders said: one day the caribou will come and it will take all your reindeer. I did not believe them [because] there were plenty of reindeer. Now the caribou have come and there is no reindeer and there is no reindeer anymore. The elders always said: they would come back. And they did."

Gibson Moto, Deering, Alaska

A similar statement that praised elders' memories was made a few years ago by an Inuit hunter from Rankin Inlet, in the Canadian Arctic, with regard to climate variations in his local area (Ernerk 1994):

> The elders do tell us that once every so many years cool summers repeat themselves, that also some years have freak snow storms that occur in mid-summer. My father told me about one such year in his memory where there was such a cold and extended snow storm in the middle of an otherwise warm summer, that this storm caused many baby birds to die, that all the mosquitoes appeared to die off and there was quite an accumulation of snow on the ground. He remembered that after the storm was over the snow melted and things did return to normal. In discussing this particular storm with my boss, Ollie Ittinuar, who is presently 70 years old he indicated to me that he remembered that particular storm. My father was at least 25 years his senior and we place this storm in the early 1930s. It was the storm and summer to remember.

5. Unlike specialized scientific research, Native knowledge is always multi-faceted and it covers a much broader spectrum of indicators of change

"We are seeing many differences in the quality of sea ice. It is less salty, easier to chop, and [it] breaks up sooner. The fast ice retreats early. It breaks up and retreats 20-30 miles and doesn't come back. We used to have ice come in in fall time, but now the water freezes up in place and we don't see the ice floes drifting to shore. Multi-year ice doesn't arrive till later."

Charles D.N. Brower, Barrow, Alaska

"The ice conditions and walrus migrations are different from my early years, as they are now. We used to go out hunting for migrating walruses in June and last part of May. We used to go after bull walruses that remained on the northern side of the island. We used to hunt them at the same time when the females with calves are migrating north. The bull walruses could go out and come back in the month of June. We cannot see them no more now in the month of June. We don't know why they are gone. Maybe this is because of too many aircrafts coming in into our area."

Conrad Oozeva, Gambell, Alaska

"There have been many unusual occurrences in recent years [in our area]. Weather patterns, fish distributions, and other things are very odd. Some species of fish have been caught in areas where they've never been seen before. There used to be a lot of tomcod in our area, but no longer, and we don't know why.

"In 1998, there was a big die-out of seabirds. Many dead birds washed up on shore. Did they die of starvation, or because the weather was too warm? Animals, too, are going to places they've never been before. Is it lack of food – or because of other reasons? Salmon are decreasing in some places. They are fewer in the Yukon River now. There are fewer clams in our area. The bay used to have lots of clams, but now there are hardly any – only very small ones. And the shellfish have moved into our area, where they used not to be."

Dale T. Smith, Sr., Mekoryuk, Alaska

6. It is often stated that "Native knowledge is intuitive and holistic" – in fact, it is very well organized around key environmental agents (such as wind or ice) or indicators of change or around critical game species

"There is much difference in sea ice that I see during my lifetime. Every year the first ice we see is mostly of this iceberg type – the floating icebergs coming from the North, mainly from the month of September. The wind always starts blowing from the North, almost regularly. I think that same high wind makes the ocean flow, too.

"And now we have more westerly winds. What I learned from my elderly people, as the days grow longer, the northwest throw [stream] gets stronger in between the island and the mainland of Siberia. But now with those more westerly winds we have more ice on the other side, the Anadyr side of the island, the ice is packed over there."

Conrad Ozeeva, Gambell, Alaska

“Our ice and weather conditions in Savoonga are probably comparable to what Gambell conditions are. The young ice was formulated when Conrad was growing up [in the 1930s and 1940s], maybe in late September. By October, the young ice was already there, because of the prevailing northern winds. The cold current is always flowing, snow is flowing; and so there was a crystallization process, because of the drop in conditions with the water temperature. What was formulated was young slush-ice. As Conrad is saying, when he was growing up, because of the north wind, these glacier icebergs, drift icebergs, were washed up on the shore of St. Lawrence Island. That was probably how the solidifying process of the young ice took place in those days.

“And as he says, we were aware about the sea icebergs flowing from the north. In late October, during Conrad’s time, that is, during the time when ice formulated in mass, it had a lulling position [impact] within the Bering Sea, where there is lots of big waves. And when the ice solidifies enough, you can actually go out hunting in 25-30-knot conditions, because the formulation of the young flat ice makes the waves gentle enough to go out for harvest activities. When it solidifies enough, when we can go on it and we have to be careful, because winter is going to happen at this time. When they were growing up, they were usually gone on the ice [in winter] harvesting walruses and bearded seals, and other species of seals. And they were actually pulling back their walrus meat with the raw-hide ropes, just sliding it through the ice. And they will bring that food home and that meat home for their families and their children, and also for their family dogs.

“When they were young, they used to go out by dog-teams [on ice] for many, many miles. And this is their perception of the winter ice conditions.

“Now, these days if we are lucky, the ice will set up at a time of late November, usually in December in Savoonga where I am from. It is like that now most of the time. This year is a perfect example. On Thanksgiving Day, that was November 25th [1999], we harvested a bowhead whale right off the village of Savoonga where the migration happened. And the next day the young ice solidified enough, it was dense enough we could not go out. Just the day before, men could go out with their skiffs and zigzag around, because there was enough open water in front of the village that they could go after the bowhead whale. The next day, when they were butchering the whale, it was too dense and solid – and that meant that winter was here. When the ice solidifies and it becomes solid, that means winter in our culture has taken place.

“In the past ten years or so, our winter trends based on the ice conditions have been probably early December to mid-December, because as I mentioned, we had all these walruses and bowhead whale in front of Savoonga. Now, Conrad knows – and he is a living database – maybe 30 different conditions of ice and snow around our island. And I just talked about two different conditions: one is slush ice and the other is flowing sea icebergs. Conrad can give you many, many different variations, with their specific terminology from our Native culture.”

John Waghiyi, Savoonga, Alaska

7. Native observers are very well trained in documenting unusual ice and weather patterns – but they have their own ways and means of memorizing and documenting the events

As an illustration, we may cite at length three narratives of St. Lawrence Island hunters of different ages about years with extraordinarily warm winter conditions in their respective communities.

George Noongwook (Savoonga, born in 1949):

“My most clear memory of ‘extreme weather’ was that of winter of 1962 [1962/1963]. This has been a really exceptional winter. I remember: it was the month of January, and then a lot of snow melted. Not all of it but most of it just melted down to the bare ground. And during that fall, that same year, there were very high winds blowing from the southeast. It was strange, because it’s normally blowing from north-northeast all the time.

“Consequently, not very many people were able to bring back home any walruses or seals or other marine mammals. It was so bad [in the village] that they had to fly in dried fish and drop it down from the airplanes, because back then we did not have an airstrip in our village. So, they dropped dried fish and other protein-rich food off the airplanes [to feed the people].

“This is the year I clearly remember as one with exceptional weather that affected all the people. We used to commemorate such events: in the old days, people would make a song or try to mark the moment somehow. Like this extreme weather conditions. One elder in our village named his son *Ughugutkaq* for that particular year. That little boy was born during this year, and the man’s name was Keengeekuk [*Kingikaq*]. Because *ughuguq* means ‘melting snow’ [in Siberian Yupik language]. This name was because of that extreme weather when the boy was born.

“It was pretty scary these days, I remember. No returning birds, nothing. When the snow melted down, there were ponds of water on the ground, but nothing else. There was almost no hunting because of these extremely dangerous conditions. We could probably go anywhere [hunting] and get almost nothing. I do not think it was safe to go out because there was still some ice at sea. My memory is probably sketchy but that I can remember. People were being blown away almost down to the water because of the high winds during the previous fall. It was scary!”

Edmond Apassingok (Gambell, born in 1963):

“As far as I can remember, it was this winter [1999/2000] that was very exceptional because of its warm weather. About a week ago or so it started to get real warm, I mean – exceptionally warm. And it continues to this day [February 16th]. But before that we had nice weather and these easterly winds; then, right after the New Year the southerly winds started to pick up. Before that it seemed like it [was going to be] a normal winter, but then it warmed up, it’s all changed.

“As far as I can remember, that did not happen in a long time. We have already spotted a bowhead whale [off Gambell] before I came to this meeting. People say, that this is very unusual, it’s too early. Also from the land observation, several bowheads have been seen – this does not happen usually in February, sightings like that, at least from my recollections. They have not seen too many walruses, but seals are quite normal – at least, since the ice came in in December. The sea ice was also late [last year] and it was strange, not like the usual year. I remember we had to go to another conference in late November, and we flew over from Gambell to Nome. When we left from Gambell, it was fairly cold but there was no young ice at this time, of this iceberg type. Usually, before the young ice comes in, these icebergs are drifting [from the north] – this indicates that the young ice is coming. But not this year! When I called home from Anchorage, people said that it's pretty windy from the north, and the young ice already came in. But there were no icebergs this year, although they always come before the young ice comes in."

George Noongwook, on 1999/2000 ice conditions:

"In Savoonga, the ice conditions were also very unusual this past fall. We even were able to get a bowhead whale right in front of our village. That happened on Thanksgiving Day, November 24th [1999]. The wind was of 25 knots, but because there was lots of ice on water, young ice, it kept the water from the winds. It got really cold then and that lasted through the whole of December. Then in January it started snowing, we did not have any snow in November, in December, and half of January. On January 11th it started snowing, and it snowed almost every day until these days. There were tons of snow. Now we have probably much more snow than usual, like the older people say – 'it's like the old times.' They have not experienced that much snow in years. It was really difficult to walk practically anywhere.

"It was this way up to February, probably up to a couple of weeks ago. And then in got real warm, real warm. At one time, one could see the ground and the snow melting. Just like springtime when the snow is melting. But there were not that many walruses like we usually see in spring. It's so strange! We had walruses in Savoonga until the month of December, and we also got that bowhead whale. The walruses were very close: maybe a mile or half-a-mile off the village. Lots of other sea mammals as well. This was because of these easterly winds.

"Now, this month [Febuary] we also managed to get a lot of open water [in front of our village] for a week or so. Right until the day we came here [February 14th], and then the ice came in again. We were even able to get out [in our boats] – there was enough of open water to get out hunting, particularly to the west, that the waves were coming from that direction. We saw six walruses at this time coming from the west; so, several boats went hunting westward, as far as *Taapghhaq*. We did not see the walruses there and there were no *makllaks* [bearded seals] either but lots of seals. And lots of birds – old-squaws, murres, like in springtime.

"In 1990 there was another exceptionally warm spring that people remembered. We were able to get our quota of four whales in one week. The temperature warmed up to 60º F on one day. There was abundance of belugas, and whales, and all kinds of birds. That was at the Southwest Cape, we call it *Pugughileq*."

Conrad Oozeva (Gambell, born in 1926):

"We always have warm weather during the winter time. Our winter, as I mentioned [is] when thin ice gets it – that's when we call it 'winter.' It was only two times, I remember, when the ice showed in before fall: one [time] in the last part of August and the other one [in] first part of September. That's all I know about these two but the ice did not get clear to the land. We even got some walruses and seals when that ice showed in in August, in last part of August. [The year] was some time in the late [19]40s or early '50s. And when the ice was in September – it might be later – '40s or '50s.

"It is common that it gets warm in wintertime. Maybe, twice or even three times until spring; sometimes, maybe, two times. Only one time I know it got real warm in January. It rained, rained, and rained, until the ice on the lake was soaked with rain and started breaking in near the shore land. It was like this all January, maybe from last part of December – it gets warm, very warm. We also had all those high swells all the time. The ice almost formed firmly but it did not [solidify], maybe, because it got too warm. And the walruses were coming in [but] there was no ice for these walruses, [and] they stayed on the east side of Gambell. So, people went hunting down by boats on ice on the other side, got the walrus, and came home. The backwash was washing in, this seafood that grows under the ocean, and other sea plants. [*Krupnik: Was it like in 1962?*] It did happen after that too but this time was farther back.

"It got snow fully on the ground but then it rained, and rained, and rained. Snow melted but shore ice was still good enough on the other side. When we wake up [in the morning] – it's still warm. Ralph [Apatiki] even asked me the question: will it ever get cold again? And I told him: "It still will be time when it gets cold!" [Laughs.] And it did in later time get cold…

"It is very common warmth like we have this winter – two or three times every year or almost every year. But those past few years we hardly had any warm weather [in winter]. The temperature got high enough, not much cold. This year was maybe the coldest I know…

"I remember being a boy, when we still had these *mengteghapik* [houses with an inner chamber of reindeer skin]. In the morning I could hear people walking making cracking noise out there, because it's so cold. We always dressed up warmly that time. I don't mind staying out there long enough. Of course, in those days, even in cold days, the days were nice and calm, almost calm. No snowing: just cold and calm. When we were still using those [oil] lamps, *naneq,* every time when I got out on a very cold day, I noticed my eye-lids are getting picky, when I am getting out first of my house. They always got picky because of the moisture inside the house. This winter reminds me of those old days.

"I know [remember], it did get real cold with some wind in my [old] days. I was going out hunting from my old house, I could not even stand it anymore because I had beginning to get frostbites. I had to stop. You have to walk long enough to get used to cold. I could not stay long enough when I was hunting on the ice – it was just too cold. So, I came home. I did not get seals or walruses [because] it was too cold. It's the same type of winter we have this year. If it happened like [in] the early days, we have this cold and windy, and snowy winter, we ran out of food. And all *naneq* [oil lamps] were down. In the days like these, there was little fuel. This year is the coldest year and [although] it got warm recently, it's still not as warm as in the old days, when it gets warm. The snow often thawed when it got warm in the early days.

"[*Krupnik: A winter without snow?*] I don't remember anything like that. One year we had a long easterly wind. The storm on one side but this side [western side of Cape Sivuqaq] was clear. It keeps so for many days, those easterly winds blowing. I could see that heavy cloud on the other side [of the cape] but no clouds on this side. And the easterly wind [was] blowing all day, maybe for a week or longer. We got snow [that year] but the snow was blown off all over. I remember because I was going to check my trap lines and foxes were very visible at that time because there was no snow, it was all blown away.

"[*Krupnik: A warm winter is called "woman-winter" by the Yupik people in Chukotka*]. Yes, I heard people saying that in Gambell too: "woman-winter," *aghnangyaq*. When the temperature is above 10º F [in winter] – I like it. Because you can tell it even without seeing the thermometer. The sea between the ice looks black, no smoke, nothing. We have a good winter this year, hunting was good even on one of those cold days. My boat has been going hunting, we have been bringing walruses, *makllak*s [bearded seals], and birds. They don't go far out too.

"This change [is visible], *anleghaq* [going out at sea, particularly to the east] has changed. When I was younger, there were these migrating walruses coming on the eastern side of Gambell first; and then they were going around the point, and headed south. That used to happen in November, first part of November. This is where we first got our walruses on the other side of the hill, when walruses are migrating south. That did not happen like that anymore. Now they do like that for very short time in December, which is late. Just enough walrus on the other side, mostly the walrus females. Something is changing, we noticed this."

Some Final Remarks

These stories and observations of Native hunters from a handful of Alaska communities illustrate that local knowledge has enormous power as a resource to document changes in weather, sea ice, and marine life due to modern climate change. What is listed here is just the tip of the iceberg of information that was shared at the meeting and has been written down, in order to give both full acknowledgement to and a better appreciation of the Native contribution to workshop. Unlike scientists, hunters are not bound in their observations by a "project time" or to any salaried research period. They are going on the ice almost every day, year after year; and they preserve their memories, listen to elders' stories as well as share their observations with other hunters. This is the body of knowledge that has been praised highly by the most experienced anthropologists and natural scientists for years (*e.g*., Freeman 1984, Nakashima 1993, Nelson 1969).

It is almost trivial these days to talk about "barriers" and "hurdles" on the ways Native or local knowledge can be matched with the data collected by the scientific community. Those obstacles most commonly listed arise from the presumption (which more often than not remains untested and never fully examined) that traditional knowledge is assumed to be intuitive, holistic, qualitative, and orally transmitted while academic or scientific knowledge is primarily analytical, compartmentalized, quantitative, and literate (Berkes 1993, Eythorsson 1993, Lalonde 1993, Nadasdy 1999). While there is some truth to these differences, both scientists *and* Native observers can effectively operate with *both types* of knowledge – as has been clearly demonstrated by the many presentations given at the Girdwood Workshop, prepared and informal alike.

It is not a different *nature* but rather a different *focus* of scientific and local knowledge that clearly keeps these two types of expertise looking in different directions. Modern scientific studies of environmental change are unmistakably *time-focused*, in that scientists are primarily looking for well-documented series or samples of otherwise uniformly organized data (like annual or seasonal temperature and ice series, ice charts, satellite photos, ice core samples, etc.). This focus allows scientists to operate with both the average and the extreme characteristics of the environment that are easily and thoroughly positioned in time (*i.e*., by fixed dates) and which are regarded as "statistically reliable." Thus, the scientific knowledge of climate change is openly fixated upon expanding the timing and reliability of the data it operates with; the very nature of data may be of secondary importance.

Local knowledge, on the other hand, is first and foremost *detail-focused*, in that it prizes specific and very detailed information about the characteristics of the environment observed, including climate change. There is no issue of statistical reliability, and every personal observation is considered sound and equal, as long as it relates to the environment, which is familiar to the given observer. The age of the observer is probably the closest equivalent of the scientific concept "reliability," as changes reported by elders are always considered more valid than those observed by younger people. And there is hardly an issue of precise timing. Local knowledge documents the many possible facets of environmental changes as well as of exceptional phenomena; but in most reported cases it is not focused on absolute dating or on any mechanism of precise timing similar to the beach-ridge chronology developed by geologists and archaeologists. This is a scientific method when events or objects are dated along the series of beach ridges that have been subsequently built on shore by the sea surf through time. That is why for many scientists local knowledge contains *too many* data that are very hard to organize properly in a standardized time series.

Therefore, in order to be compatible, both types of knowledge must be substantially modified to accommodate each other's specifics – in the same way that the data from social and natural (physical) sciences have to undergo certain accommodations to be used in any interdisciplinary or joint study. One can see this conclusion as one of the major outcomes of the Girdwood workshop and one of the most critical by-products of a three-day intellectual (inter-knowledge) interaction.

One can also see from the statements of many Native participants that local hunters are far more advanced in mastering the terms, data, and approaches developed by scientists than vice versa. Unlike Native observers, scientists learn through "projects" and they respond to new challenges by "research programs." Therefore, the only way academic science can modify itself to be more open for accommodation of Native knowledge is by developing a special research program on just how to do this.

This approach differs from the many previous studies focused on the incorporation of traditional knowledge into scientific research, including the very original assumptions we shared while organizing the Girdwood workshop. Scientific knowledge about recent climate change in the Arctic has to become detailed and specific. From the abstract global models, it has to be projected down to the regional and even to the individual village level in order to interact productively with the knowledge and observations of change shared across local communities. For local knowledge, a timing mechanism has to be created in order to make Native observations of past and present events compatible with the records kept by academic science. This is a complicated enterprise, as each local community has to build a "beach-ridge chronology" of its own, one based upon its particular history, available documentary records, and memories shared by the most elderly experts.

To accomplish these and other goals, much joint research as well as intense mutual interaction and knowledge/data sharing is required. This future long-term effort should be focused first and foremost on charting the ways for *mutual adjustment* of the two types of knowledge of Arctic climate change. When and if such a program gets the necessary funding, it may well become the most significant legacy of the Girdwood workshop of 2000.

Acknowledgements

This paper came about as a spontaneous product of the Girdwood workshop, as we all realized that a lot of extremely valuable data could be lost unless they were recorded and put on paper. Rob Mattlin of the Marine Mammal Commission and Henry Huntington were particularly helpful in supporting this effort as were many Native participants who let us document their personal observations and perspectives. I am also grateful to Henry Huntington and George Noongwook for their extremely valuable comments and advice offered upon reading the first draft of this text. The shortcomings in presenting a summary of what was said and what we all learned during the Girdwood sessions are all mine.

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Appendix 1: Observations of Recent Environmental Change in Alaska Native Communities in the Bering Strait-Chukchi Sea Area

Category	St. Lawrence Island	Norton Sound-Nunivak Island	Kotzebue Sound	Point Hope-Barrow
Unusual Sightings	-Stranded dolphins -Sharks in seal nets (Greenland?)	-Stranded dolphin (Elim) -Minke whales off Nunivak Island -Narwhale seen between Cape Denbigh and Cape Darby, spring 1999 -"Small" ringed seal caught in Jan. 1999 -Minke whales seen off Unalakleet, Elim -Coyote in Golovin	-Bowheads seen off Deering -Same shark in Deering -Minke whales and dolphins off Deering -Stranded dolphin in Kivalina ~ 1998 -Humpback whale off Kivalina ~ 1990 -Spotten seal in Kivalina ~June 1999	
Changes in Physical Condition of Game Species	-Walruses: thick blubber this year	-Fewer or no clams around Nunivak Island, very small specimens only	-Migrating caribou are thin	
Early Seasonal Timing	-Bowheads seen in early February, 2000	-Oldsquaw seen in February	-Salmon coming earlier, when there is still ice -Gray whales seen off Kivalina, May 1995 (very early) -Killer whales seen in June 1999 (very early)	-Bowheads seen off Point Hope in February (very early)
Late Seasonal Timing	-Walrus and bowhead seen off northern coast in late November 1999	-Gulls seen in December		

Category	St. Lawrence Island	Norton Sound-Nunivak Island	Kotzebue Sound	Point Hope-Barrow
Changing Speed of Animal Migration	-Walrus used to concentrate eastward from Gambell for the full month of November but now for one week in December			
Unusual Animal Behavior	-Seal eating by walruses that are not typically "rogue" walruses	-If no ice, walruses haul out at Cape Darby -Mass die-off of seabirds around Nunivak Island		
Physical Changes in Habitat	-Shorefast ice melting very rapidly -Sea and lake levels rising -No floating icebergs coming in during the fall ice formation -Winter ice solidifies at least one month later -Active beach erosion on the southern side; old camps and sites under water	-Old timber washed away by frequent storms and beach erosion (southern Seward Peninsula) - Very warm spring weather, quick ice melting in recent years; unstable sea ice -Berries ripen earlier		-Earlier breakup, less salty sea ice -Late arrival of multi-year ice, no iceberg floating in in the fall; water freezes in place (Barrow)

Category	St. Lawrence Island	Norton Sound-Nunivak Island	Kotzebue Sound	Point Hope-Barrow
Increase in Abundance	-More spectacled eiders -Increase in sculpin -Humpback whales feeding off Gambell	-Caribou migrating to Seward Peninsula -Beluga increasing in Nome District -Herring -Halibut	-Caribou coming into Deering; huge caribou herds around Deering, Buckland and Shishmaref -More species of marine mammals (minke whale) -Walrus increasing (Deering) -More minke whales off Kivalina	
Decrease in Abundance	-Fewer oldsquaw and sandpipers	-Fish stocks at low level -Geese stock declining (Nunivak Island) -Fewer salmon in the Yukon River -No tomcod off Nunivak Island	-No/few bearded seals near Deering -No ringed seals on spring ice (off Deering, 1999) -Fewer salmon in 1999 (Deering) -Pretty stable (Kivalina): depends on ice conditions	
Changes in Seasonal Human Activities	-No more hunting for walrus bulls in June -Later fall boat hunting in Savoonga; fall bowhead harvested for the first time in 1999	Spring seal hunting in boats (April) in northern Norton Sound		

Appendix 2. Yupik Terminology for Major Sea Ice Conditions and Types of Sea Ice off St. Lawrence Island, Alaska (provided by Conrad Oozeva)

DANGEROUS SPOTS

Alqimiin
Aygughnin
Imangesleq
Ngaayuun
Nuyileq
Pequ
Qanigvik
Qateghrapak
Siinguraq
Tepaan
Tuviilleq
Ugmetaghaq
Uulsugnaq

EDGE OF SHORE ICE

Ighighneq/Ighighlleq
Iitga
Kangighin
Kangin
Laaq
Luughek
Sanineq
Tekeghin

CAKE ICE

Iighwilkaaq
Iighwilnguq
Ilulighaq
Sikuqwaaghpak
Sikuqwaaq
Ughvuneq

BROKEN ICE

Ayemqutek
Aygughnin
Kaawraneq
Kagimleghwaaq/Kagimleq
Qelughtaaq
Qerngayaak
Tunglu
Tungzighaq

LAYERED ICE

Amaghileq
Qaspighun

BEST TO WALK ON

Umughagek
Umughak
Sigiin

COVERING ICE

Nasaghuk
Qayemgu
Sikughnak

NEW ICE FORMS

Pugsaqa
Qenu
Qenughhaghaq
Saagsiqu
Sallegpak
Sallek
Sallgaaq

SAFE TO WALK ON BUT DANGEROUS

Allungelquq
Amaghlleq
Kaspigpak
Kaspik
Kaspikengeltaq
Nevesqaghneq
Pequ
Qagin/Qagitek
Qaspighun
Qenghuk
Ughuun

CLIMATE CHANGE AND ITS IMPACTS ON THE ARCTIC ENVIRONMENT

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Abstract

Regional assessments of climate change and its impacts are a high priority in the international programs on global change research. In the Arctic, climate models indicate an amplification of the global greenhouse warming, but the observed high-latitude climate trends over the last few decades are much more regional and patchy than predicted by the models. While considerable uncertainties remain in the long-term prediction of change there is some agreement between model results and observed trends by season on shorter time scales. The warming observed over the landmasses of the Arctic over the last few decades is matched by corresponding observed decreases in snow cover and glacier mass balances, by thawing of the permafrost, and by reductions in sea ice extent and thickness. Vinnikov *et al*. (1999) state that the probability of the observed trends resulting from natural climate variability is less than 0.1 percent for the observed 1953-98 sea ice trends. This evidence strongly suggests that the observed decrease in northern hemisphere sea ice extent is related to anthropogenic global warming. While uncertainties exist about the future, climate change in the Arctic during the past few decades has clearly had major impacts already on the Arctic environment which will become much more pronounced if present trends continue.

Introduction

The Arctic plays a crucial role in global climate change. It is a sensitive indicator of change and its snow and ice features are good integrators of change. It also stores long-term climatic records in its glaciers and the Greenland ice sheet. The Arctic also affects the global climate directly through interactions between its atmosphere, ice cover, and oceans, and through a number of important feedback processes. Practically all climate models predict an amplification of the global greenhouse effect in the Arctic (Intergovernmental Panel on Climate Change 1990, 1996, Everett *et al*. 1997).

Global greenhouse warming affects the Arctic environment by melting ice and thawing permafrost. Practically all the snow and ice features of the Arctic will be affected in one way or another. The extent and thickness of the seasonal snow cover, sea ice, permafrost, glaciers, and river and lake ice are all expected to decrease as the climate warms (see Figures 1-4). These changes, in turn, will affect the polar ecosystems with their distinctive fauna and flora. Socio-economic consequences to populations, industry, and lifestyles will be inevitable. Not all of these changes are necessarily negative; for example less sea ice may allow the opening of trans-Arctic shipping routes and offshore petroleum exploration (Weller 1998).

The Arctic, in turn, can affect the global climate through polar feedback processes. The albedo-snow cover-temperature feedback (Kellogg 1975) is one of the main causes of the amplification of the greenhouse effect in the Arctic. Permafrost-trace gas-temperature feedbacks could also be important. If more CO_2 and CH_4 are released when permafrost thaws, this will increase the atmospheric temperature and will result in thawing more permafrost. Melting of glaciers and ice sheets raise the global sea level, and the collapse of large ice sheets has been postulated as a possibly trigger of the major, rapid climate changes during the last ice age, as seen in the Greenland ice core results (Alley *et al*. 1993).

Projected Future Climate Impacts

The Intergovernmental Panel on Climate Change (IPCC) report *Climate Change 1995* (1996) includes a chapter (Chapter 7 of Working Group II on the cryosphere – the regions of snow and ice) on climate change and its likely impacts on the polar regions. This assessment states the degree of confidence that the IPCC had in its predictions, which include the following:

- Many components of the cryosphere are sensitive to changes in atmospheric temperature because of their thermal proximity to melting. The extent of glaciers has often been used as an indicator of past global temperatures (High Confidence).
- Projected warming of the climate will reduce the area and volume of the cryosphere. This reduction will have significant impacts on related ecosystems, associated people and their livelihoods (High Confidence).
- There will be striking changes in the landscapes of many high mountain ranges and of lands at northern high latitudes (High Confidence). These changes may be exacerbated where they are accompanied by growing numbers of people and increased economic activities (Medium Confidence).

For a scenario that doubles the atmospheric concentrations of CO_2, the following changes and associated impacts on the Arctic are likely, again listing the degree of confidence in these predictions:

- Pronounced reductions in seasonal snow, permafrost, glaciers, and periglacial features with a corresponding shift in landscape processes (High Confidence).
- Increases in the thickness of the active layer of permafrost and the disappearance of most of the ice-rich discontinuous permafrost over a century-long time span (High Confidence).
- Disappearance of up to a quarter of the currently existing mountain glacier mass (Medium Confidence).

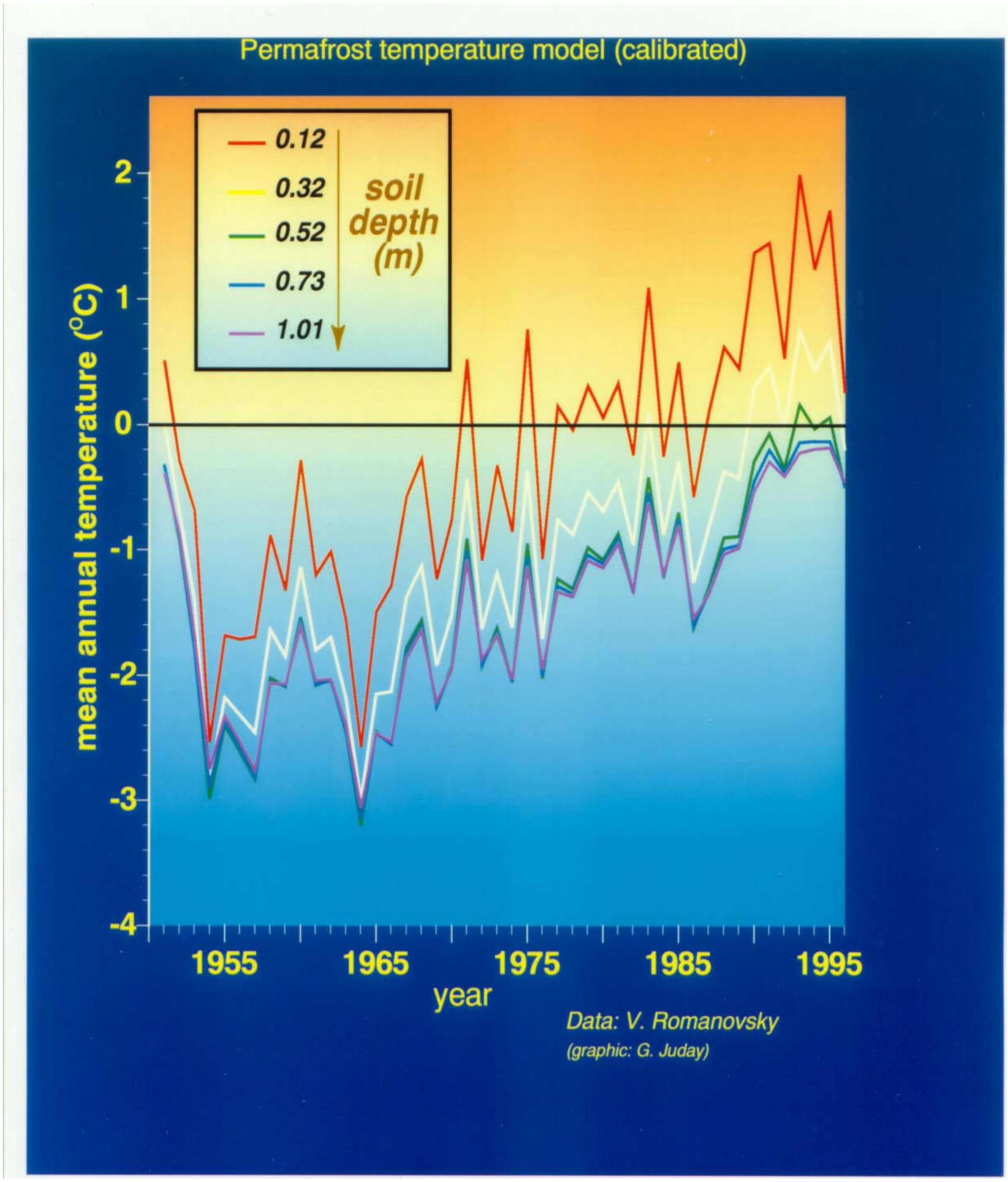

Figure 1. Change in soil temperature at various depths in permafrost terrain at Fairbanks, Alaska (V.E. Romanovsky, University of Alaska Fairbanks, personal communication, 1999). (Reprinted with author's permission.)

- Less ice on rivers and lakes. Freeze-up dates will be delayed, and break-up will begin earlier. The river-ice season could be shortened by up to a month (Medium Confidence).
- A large change in the extent and thickness of sea ice, not only from warming but also from changes in circulation patterns of both atmosphere and oceans. There is likely to be substantially less sea ice in the polar oceans (Medium Confidence).

Many of these impacts are already being experienced in the Arctic, as shown in the next section.

Evidence of Climate Change

Twentieth Century Climate Trends

Discussion of the detection of the greenhouse signal in the polar regions usually revolves around two questions: (1) Are we now seeing the greenhouse signal in the high latitudes? (2) If not, how and when will the signal manifest itself? Chapman and Walsh (1993) examined the climate trends in the Arctic for the period 1961-1990, using the climate data set of the Climate Research Unit of the University of East Anglia (Jones *et al*. 1986). Their analysis, as well as their updated results for 1966-1995 (unpublished), indicates considerable warming over the landmasses of Eurasia and North America, particularly in winter and spring. Over the last three decades, trends towards higher temperatures have been up to 1.5^{o}C per decade. On the other hand there are also smaller areas of cooling of similar magnitude within the Arctic regions, particularly in the South Greenland and Davis Strait areas.

The available data also point to a more vigorous atmospheric circulation associated with a deepening of both the Icelandic and Aleutian Lows (Maxwell 1995). The primary reason for a warmer climate in the Western Arctic, for example, is that more southerly flow occurs in winter coupled with less northerly flow of cold air from Siberia. Similarly the cooler climate in Southern Greenland is most likely related to a shift in the circumpolar wave pattern with increased northerly flow in that region. Whether this is triggered by the greenhouse effect is not clear at present.

Impacts on Snow and Ice

In many different parts of the world, pronounced reductions in seasonal snow, glaciers, permafrost, and sea ice have been observed as a consequence of a warmer climate. In the Arctic, where the following observations have been made, these changes are particularly pronounced. Vinnikov *et al*. (1999) state that the probability of the observed trends resulting from natural climatic variability is less than 0.1 percent for the observed 1953-98 sea ice trends. This strongly suggests that the observed decrease in northern hemisphere sea ice extent is related to anthropogenic global warming.

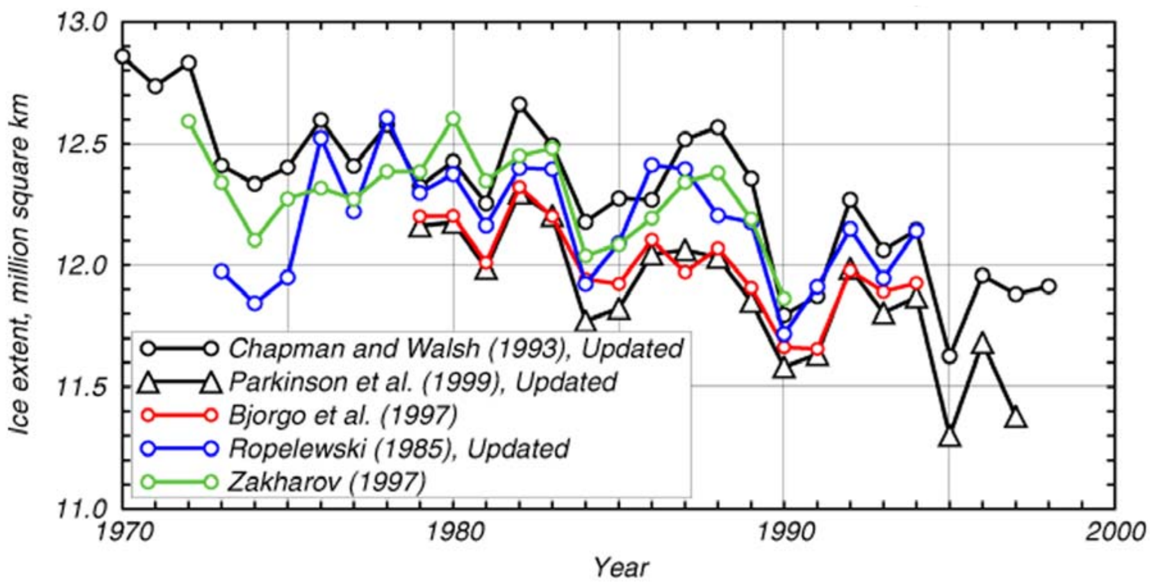

Figure 2. Observed decrease of Northern Hemisphere sea ice extent during the past 25 years. (Reprinted with permission from Vinnikov *et al*. 1999, copyright 1999 American Association for the Advancement of Science.)

Sea Ice:
There have been substantial reductions in both ice extent and thickness in the Arctic in recent decades:

- The most recent study using passive microwave data from satellites for the last two decades has shown Arctic sea ice extent decreasing by 2.9% (+/- 0.2%) per decade (Cavalieri *et al*. 1997).
- New extreme minima of summer ice extent have been established repeatedly since 1980. The September ice extent in the Beaufort and Chukchi seas since 1980 was 25% below the prior minimum value over a 45-year record (Maslanik *et al*. 1999).
- Sea ice extent in the Bering Sea has been reduced by about 5% over the last 40 years, with the steepest decrease occurring in the late 1970s (Bering Sea Impact Study 1997).
- Sea ice thickness, a sensitive indicator of climate change, has decreased by about 1.3 m, from 3.1 m to 1.8 m, in most of the deep water portion of the Arctic Ocean between the 1960/1970s and the 1990s, based on submarine sonar records (Rothrock *et al*. 1999).
- The sea ice thickness decrease is greatest in the central and eastern Arctic and less in the Beaufort and Chukchi seas (Rothrock *et al*. 1999).
- Observations at Barrow, Alaska, on the Beaufort Sea coast, showed sea ice to be only 1.4 m thick in 1998, compared with its normal thickness of 1.7-1.8 m; this is thinner than ever observed before (L.H. Shapiro, University of Alaska Fairbanks, personal communication, 1999).

Fig. 3. Sea ice thickness reductions for various regions of the Arctic from submarine data collected between 1958-1976 and 1993-1997 (Rothrock *et al*. 1999). (Reprinted with author's permission.)

Glaciers and Ice Sheets:

- Glaciers in the Arctic and subarctic regions have generally receded, with typical ice-thickness decreases of 10 m over the last 40 years, but some glaciers have thickened in their upper regions (Bering Sea Impact Study 1997). A warming of 1°C, if sustained, appears to reduce glacier lengths by about 15%.
- The mass balance of Greenland is still uncertain, but there appears to have been a tendency towards increased melt area between 1979-1991 that ended abruptly in 1992, possibly due to the effects of the Mt. Pinatubo eruption (Abdalati and Steffen 1997).
- Balances have been positive for European glaciers in Scandinavia and Iceland due to increased winter precipitation (Serreze *et al*. 1999).
- Over the period 1961-1990, small melting glaciers worldwide have contributed about 7.36 mm to sea level rise, with the Canadian High Arctic Islands contributing 1.36 mm, Alaska 0.54 mm, and Asia 3.34 mm (Serreze *et al*. 1999).

Seasonal Snow Cover:

- Cyclone and anticyclone frequency has increased over the Arctic between 1952-1989 (Everett *et al*. 1997; section 3.2).
- Annual snowfall has increased in the same period over Northern Canada (North of 55^{o}N) by about 20% and by about 11% over Alaska (Everett *et al*. 1997; section 3.2).
- While there is more snow in winter, satellite records indicate that since 1972 northern hemisphere annual snow cover on both continents has decreased by about 10%, largely due to spring and summer deficits since the 1980s (Serreze *et al*. 1999).
- There has also been a decrease in snow depth in Canada since 1964, especially during spring, whereas winter depths have declined in some areas over European Russia since the turn of the century, but have increased in others (Serreze *et al*. 1999).

Permafrost:

- Borehole measurements in continuous permafrost have shown warming of up to 2-4°C in northern Alaska over the last 80-100 years (Lachenbruch and Marshall 1986).
- Discontinuous permafrost throughout Alaska has warmed, and some of it is currently thawing from the top and bottom (Osterkamp 1994).
- Near-surface permafrost has also become warmer by 0.6-0.7^{o}C in Siberia during the period 1970-1990; this warming may in part be due to a deeper snow cover in winter (Pavlov 1994).

River and Lake Ice:

- River and lake ice formation in Alaska occurs later in fall and breakup occurs earlier in spring, leading to shorter ice-covered periods. The annual breakup of the Tanana River ice in interior Alaska has been recorded since the 1920s and shows most breakup dates to occur in April in the 1990s compared with most of them occurring in May in the 1920s (Nenana Ice Classic 1999).

Fig. 4. Glacier mass balance changes in Western North America from 1957 to the mid-1990s (Sapiano *et al*. 1998). (Reprinted with author's permission.)

Fingerprinting Climate Change

A view that has been proposed by climate researchers is that the "traditional" emphasis on sea ice extent and Arctic Ocean air temperatures as early indicators of change should be replaced with a broader "fingerprint" of many variables. This fingerprint should involve information from ice cores, sea ice concentration and thickness, sea surface temperatures, subsurface polar ocean temperatures, and high latitude precipitation. The set of variables in Table 1 summarizes the evidence of recent changes and provides such a fingerprint. The observed changes are consistent with those anticipated from greenhouse influences. However, there are still problems since long records exist only for surface temperatures, and even these are not long enough to distinguish unambiguously the natural and man-made influences (Walsh *et al*. 1996).

Societal and Economic Impacts of Climate Change

The societal and economic consequences of climate change in the Arctic are likely to be substantial but are not the subject of this paper. Reference to these impacts can be found in a number of publications (Bering Sea Impact Study 1997, 1998, 1999, Weller and Lange 1999). Changes in the cryosphere, as a consequence of a warmer climate, that will lead to social and economic impacts have been summarized by the IPCC as follows:

- Widespread loss of discontinuous permafrost will trigger erosion or subsidence of ice-rich landscapes, change hydrologic processes, and release carbon dioxide (CO_2) and methane (CH_4) to the atmosphere (High Confidence).
- Cryospheric change will reduce slope stability and increase the incidence of natural hazards for people, structures, and communication links. Buildings, other structures, pipelines, and communication links will be threatened (High Confidence).
- Engineering and agricultural practices will need to adjust to changes in snow, ice, and permafrost distributions (High Confidence).
- Thawing of permafrost could lead to disruption of petroleum production and distribution systems in the tundra, unless mitigation techniques are adopted. Reduced sea ice may aid new exploration and production of oil in the Arctic Basin (High Confidence).
- Improved opportunities for water transport, tourism, and trade are expected from a reduction in sea, river, and lake ice. These will have important implications for the people and economies of the Arctic (Medium Confidence).

Table 1. Summary of Changes Observed in the Arctic over the Last Few Decades of the 20th Century (modified from Walsh *et al*. 1996).

PARAMETER	TREND	COMMENTS
Surface Temperature	Generally warmer	On land, in winter/spring, but also some areas of cooling; unclear over Arctic Ocean
Tropospheric Temperature	Warmer	Lowest layers
Stratospheric Temperature	Colder	Summer only
Precipitation	Increased	Over land, unknown over sea ice
Extreme Weather	Not yet assessed	
Ocean Temperature	Warmer	Central Arctic
Snow Cover Extent	Reduced	Eurasia, in spring; also in Canada and Alaska
Snow Cover Depth	Reduced	
Sea Ice Extent	Reduced	Throughout the Arctic
Sea Ice Thickness	Thinner	Throughout the Arctic
Ice Sheet Elevation	Higher	S. Greenland, no change in Canada
Ice Sheet Surface Melting	Increased	S. Greenland
Ice Shelf Extent	Reduced	Canada
Permafrost Extent	Reduced	Alaska, Canada, Siberia

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HUMANS IN THE BERING STRAIT REGION: RESPONSES TO ENVIRONMENTAL CHANGE AND IMPLICATIONS FOR THE FUTURE

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The Presence of Humans in the Bering Strait Region

The presence of early man in the Northern Bering Sea/Chukchi Sea region and the key role this area played in the prehistory of both North America and Siberia has been recognized at least since the late 1800s. However, it was not until the 1930s and the 1940s that our understanding of both the timeline of the first human occupations and the sequence of local archaeological cultures were formalized as they basically remain today.

The idea of a land bridge across the shallow waters of the Bering Sea, which once connected Northeast Asia and North America, was originally proposed by George Dawson and some other geologists of the late 1800s (Easton 1992). Anthropologists were fast to use this “land-bridge” scenario in their quest for traces of the early peopling of the Americas from Asia. The Jesup North Pacific Expedition of 1897-1902, designed by Franz Boas, was the first attempt to survey cultures and maritime economies of native people living along the Bering Sea/Chukchi Sea coast. In 1937, an American botanist, Eric Hulten, introduced a hypothesis that argued for a continuous ice-free land mass exposed in place of the northern Bering Sea and southern-central Chukchi Sea during the glacial epochs, due to a lower sea level. He named this land bridge from Siberia to North America “Beringia” (Hopkins 1967, 1996). Further studies confirmed that such a Beringian land bridge had been exposed as an ice-free corridor on several occasions during the Pleistocene era and that prehistoric fauna and humans from Northern Eurasia had used it to enter North America. The last time Beringia was created was between 22,000 and 17,000 years ago when sea level worldwide dropped to 120 m lower than at present, and the floors of the Bering and Chukchi Seas were exposed as a broad, grass-covered plain (Dumond and Bland 1995).

This plain began to be flooded due to post-glacial warming about 15,000 years ago (BP), until Beringia was completely covered with water by 6,000 BP. By this time, the Bering Strait was firmly in place as the key channel for water circulation and for annual marine mammal migrations between the North Pacific and the Arctic Ocean (Ackerman 1988). Local ice and weather regimes that featured shore ice formation and pack ice advances into the central and southern Bering Sea in winter and the subsequent retreat of ice to the northern Chukchi Sea in summer were established. Those processes underwent only moderate changes during the following 6,000 years.

Many archaeologists and physical anthropologists argue that prehistoric humans crossed the Beringian bridge from Siberia to North America on several occasions and that they might have used both inland and coastal routes. Almost everyone agrees that the post-Pleistocene flooding of Beringia has destroyed most of the prehistoric records, particularly in what are now the shelf zones of the Bering and the southern Chukchi Seas. Earlier theories advanced a three-wave scenario, with one coastal and two inland movements from northern Siberia to North America (Turner 1988). Later studies argued for several consecutive entries (e.g., Fortescue 1998), where the most recent analysis introduces at least four major population waves: two inland and two coastal ones (Brace and Nelson 1999). Of the latter, the earlier one presumably originated in northern Japan around 12,000 years ago. It might have brought canoe-using, seafood-exploiting people all the way across the ice-free coastland of the (then) North Pacific to present-day British Columbia and Washington State, and then down to the southernmost tip of South America. The second coastal wave did not come until several thousand years later and, most probably, under a much harsher, ice-bound environment. It might have brought to the northernmost North Pacific and, later, to the Western Arctic people who already possessed skin boats, sea-mammal hunting traditions, and ice fishing technologies that were critical to adaptation to the environment, which was quite similar to the present-day Bering Sea/southern Chukchi Sea ecosystem. These people most probably were the ancestors of the modern Inuit and Chukchi as well as of the more southerly Koryak and Aleut (Brace and Nelson 1999).

Modern archaeology offers ample evidence to support these scenarios, particularly the idea of established human use of marine resources of the coastal/shelf zone of the North Pacific as early as 10,000 years ago (McCartney *et al.* 1998). The Chuck Lake site on Heceta Island (off Prince of Wales Island) in southern Alaska reveals early human occupation from about 8,100-8,300 years ago. This group supported itself by extensive exploitation of the marine environment, including mollusks, fish, sea birds, and marine mammals; evidently, it possessed boats and the necessary navigation skills (Ackerman *et al*. 1985, Easton 1992). The earliest evidence of prehistoric maritime adaptation within the Bering Sea region proper comes from the Anangula Blade site on Anangula Island in the eastern Aleutian Islands (Laughlin 1967). The site dates back to the same warming phase of roughly 8,750 to 8,250 BP. Its location on a bluff overlooking the water passage that even these days remains the key path for migrating marine mammals, such as whales and seals, from the Pacific Ocean into the Bering Sea suggests an economy based on marine resources (Ackerman 1992, Laughlin 1967).

A more sophisticated coastal adaptation, with full-scale and reliable fishing and hunting for marine mammals, progressed in the ice-free waters of the open North Pacific and the Aleutian Islands. It was enhanced by a milder local climate and greater availability of the diverse and abundant marine resources. Along Kodiak Island and the adjacent Pacific coast of the Alaska Peninsula, several sites dated to about 6,000 BP yield ample faunal remains. Those include bones of harbor seals, porpoises, sea otters, Steller sea lions, various waterfowl species and albatrosses, and fishes such as salmon, cod, and halibut (Dumond and Bland 1995). A slightly later site on Anangula Island, dated to 5,500 BP, also produced bones of harbor seals and sea lions as well as Pacific cod and halibut. On the Asian side, evidence for year-round coastal maritime adaptation comes from the winter ice-free zone of northern Hokkaido. Here several sites dated between 6,000 and

7,000 BP yield bones of sea lions, fur seals, dolphins, seals, and even whales, as well as several fish species (Dumond and Bland 1995). As in North America, hunting was done with barbed harpoons and spears; but there are still few clues to identify the type of boats and other hunting and fishing equipment that were used.

As noted above, the development of maritime hunting economies along the high-latitude shores of the northern Bering Sea and southern Chukchi Sea, areas that are seasonally covered with fast ice, did not arrive until some 2,500-3,000 years later. In the Asian (Siberian) sector, the earliest evidence of occupation of the ice-bound coasts comes from Wrangel Island, located at 71ºN, far above the Arctic Circle (about the same latitude as Barrow), in the western Chukchi Sea. Excavations at the Devil's Gorge (*Chertov Ovrag*) site produced midden pits full of fractured walrus bones as well as those of bearded and smaller seals, and birds. Several artifacts made of walrus ivory were also found, including toggle head harpoons (Dikov 1988). It might well be the earliest known proof of human use of the Pacific walrus – either by active offshore hunting with toggle head harpoons or by killing animals on shore and ice with spears and lances. Wrangel Island, with its several large haul-outs, could also offer enormous food and ivory supplies in terms of beached and naturally perished walruses.

In Alaska, the earliest known evidence of successful occupation of the ice-covered coastline (about 3,300-3,500 years ago) also comes from fairly northern areas. The first local prehistoric culture with established maritime hunting for small seals, bearded seals, and white whales (*belukha*), is named Choris, after its largest coastal site at Choris Peninsula, near the present-day town of Kotzebue. A slightly later cultural complex (some 3,300 years ago) known as Old Whaling was discovered from remains from Cape Krusenstern near the village of Kivalina in northwestern Alaska. Certain tools of the Old Whaling culture – such as the lance, large harpoon heads, and long-bladed butchering tools, as well as a litter of whalebones – provide the earliest evidence of Arctic whaling (Anderson 1984, Giddings and Anderson 1986). Pieces of prehistoric walrus ivory were abundant at the site but no walrus bones were found. This suggests that the Old Whaling people either traded for ivory or traveled to other parts of Alaska to hunt walrus. Later prehistoric coastal cultures of western and northwestern Alaska (between 2,500 and 1,500 years ago) are known as Norton, Ipiutak, and Near Ipiutak. They all possessed sophisticated seal-hunting equipment, knives for butchering, scrapers for working hides of marine mammals, and clay and stone oil lamps used for light and heat. Early Alaskan coastal hunters also made extensive use of walrus ivory (either from hunted or beached walruses) for their hunting tools, house implements, art carvings, and highly decorated burial objects, such as masks (Anderson 1984; Larsen and Rainey 1948). Few walrus bones, however, were found at these early sites, which, again, suggests a fairly limited hunting pressure on the walrus population and the widespread use of beached animals or traded ivory.

On both sides of the Bering Strait, in northern Alaska and northeastern Siberia alike, these early maritime cultures (Choris, Norton, Ipiutak, etc.) were succeeded around 2,200-1,500 BP by people who were presumably direct ancestors of the historic Inuit (Iñupiat and Yupik Eskimo) and maritime Chukchi. These people lived in year-round coastal villages and they possessed the technology and knowledge for effective year-round sea mammal hunting along both the open and ice-bound coasts. They used sophisticated toggle-head harpoons, seal-skin floats, killing lances, and skin boats. Their economy was fully based on successful hunting for walrus, various seals, and, most probably, for whales (Arutiunov and Fitzhugh 1988). They had dogs, used marine mammal oil for heating and cooking, and were skilled in making underground ice-cellars to store large surpluses of sea mammal meat and blubber. This allowed them to last through several months of ice-covered sea during the harsh Arctic winter.

They built their villages on cliffs and spits and they also settled on many offshore islands, such as St. Lawrence and Big and Little Diomede Islands. Their villages were established at sites later recognized as the best walrus and seal hunting locations, such as Sivuqaq (Gambell), Kukulik, Punuk Islands, and Kialegaq on St. Lawrence Island; Uelen, Ekven, Inchoun, Sighinik, and Kolyuchin Island on the Chukchi Peninsula; and Kingegan (Cape Prince of Wales), Cape Krusenstern, Cape Nome, and Little Diomede Island in Alaska. Their extensive use of walrus ivory, baleen, and sea mammal bones for hunting and domestic implements proved beyond any doubt that these people were indeed efficient open-water and sea ice hunters rather than opportunistic harvesters of beached marine mammals.

With these developments, a year-round maritime economy became firmly established in the northern Bering Sea/Chukchi Sea area, relying heavily on year-round sea mammal hunting and supplemented by fishing, land game and bird-hunting, and plant gathering. The only further transition of major importance was the development of communal whaling for baleen whales from large skin boats, most likely around 1,000 years ago (Bockstoce 1976, Mason and Gerlach 1995). The expansion of whaling reportedly triggered population growth and the building of larger settlements at certain conveniently located sites. This, in turn, encouraged stronger social bonds and the emergence of larger social units (such as tribes or regional societies), with their sets of institutions promoting hunting cooperation, kin solidarity, warfare, and transmission of knowledge and communal rituals. Large whaling villages—such as Tikigaq (Point Hope), Utqiagviq (Point Barrow), and Kingikti (Wales) in Alaska; Ungaziq, Masiq, Nevuqaq (Naukan), Oleq (Uelen), and Sigheneq in Siberia; and Sivuqaq (Gambell), Pugughileq, and Kukuleq on St. Lawrence Island—grew at the sites facing spring ice-leads and polynyas along bowhead whale migration routes. These sedentary coastal villages housed several hundred year-round residents organized in large kin groups, with dozens of skin boat crews engaged in cooperative hunting.

The second major technological breakthrough came with European contact (first with the Russians in the 1700s, later with the Americans after 1850). This contact introduced iron weapons and, later, firearms, wooden boats with sail, darting- and shoulder-guns for whaling, and, eventually, outboard motors. The new technology made a dramatic impact upon both the efficiency and techniques of native marine mammal hunting. Nevertheless, neither the foundation of native reliance upon the key sea mammal species, such as walrus, whales, and seals, nor the core of native tactics for hunting in ice leads, on ice floes, and in open water was altered profoundly. In many ways, today’s network of native techniques, knowledge, and skills used in subsistence ("traditional") hunting in the ice-bound coastal and shelf zone of the northern Bering Sea and southern Chukchi Sea is a direct descendant from the pre-contact indigenous coastal cultures of the region.

Past Human Responses to Environmental Change and Implications for Future Changes

There is an abundant stock of academic literature and research with scientific documentation of past human responses to environmental change across the northern circumpolar region. Since the Girdwood workshop addresses changes in sea ice and other components of Arctic ecosystem, the present review covers mainly native people and communities along the Arctic coastline. Their economies were focused primarily upon the exploitation of marine resources associated with the ice-bound coastal zone or with the seasonally retreating front of Arctic pack ice. The survey below is limited to the northern Bering Sea/Western Arctic area, though similar sets of scientific documentation are available for the Eastern (Canadian) Arctic, Greenland, and the Arctic portion of Northern Eurasia.

<u>Archaeological Record</u>

Since the 1960s and particularly during the 1970s, archaeologists were eager to look for past climatic fluctuations in search of clues to well-documented changes in prehistoric Arctic cultures and the ways native people exploited maritime resources associated with sea ice. This new environmental framework tended to be more integrative than several earlier interpretations; the latter traced basic human transitions in the Arctic to migrations, diffusion, displacement, or progressive shifts in technology and/or cultural values.

The impetus for such environmentally focused models came initially from Greenland (Vibe 1967), the Aleutians (Black 1966, Laughlin 1967, 1976), and the Eastern Canadian Arctic (Barry *et al*. 1977, Dekin 1972, Fitzhugh 1972, McGhee 1972, Taylor 1965). It soon embraced the northern Bering Sea/Western Arctic region, Alaska and the adjacent Siberian coast across the Bering Strait, as well. Several hypotheses have been advanced that feature a leading role for climate change in general and for changes in sea ice in particular in major prehistoric transitions. The most popular models included:

- Progressive shifts from inland-oriented caribou hunting economies to a more developed coastal maritime lifestyle around 3,600 years ago, and again, around 2,000-2,500 years ago in the area adjacent to the Bering Strait in both Alaska and Siberia (Bockstoce 1973, Anderson 1980, 1984, Giddings and Anderson 1986, Lutz 1982);
- Transition from the Birnirk fast-ice winter seal-hunting culture in northern Alaska and the Chukchi Peninsula to the Thule/Punuk complex, with its heavy dependence on communal spring whaling from skin boats in ice-leads, *polynyas*, and open water, around 1,000 years ago (Arutiunov 1975, Bockstoce 1979, Stanford 1976);

- Expansion of the Arctic whaling complex and an advance of prehistoric Thule Eskimo whalers from northern Alaska into the Central Canadian Arctic around 800-1,000 years ago, due to more developed spring ice-lead system and the reduction of summer pack ice. That allowed Western Arctic bowhead whale population to move earlier in spring and in greater numbers from the Bering Strait to northern Alaska and then to the Canadian Arctic, with Thule Eskimo whalers following the lead (McGhee 1969-70, 1972, 1984, Bockstoce 1976, McCartney 1977, Anderson 1981);
- Decline or extinction of Thule Eskimo whaling during the Little Ice Age 300-500 years ago in many areas of Arctic Canada, Alaska, and Siberia, due to a much colder climate, the advance of pack ice, more drift ice, and closing of major channels and ice-leads in the Central Canadian Arctic and in the Beaufort, Chuckhi, and East Siberian Seas (Anderson 1981, Arutiunov *et al*. 1982, Jordan 1989, McGhee 1984).

Though quite compelling, those early climatic models of the 1970s and 1980s soon came under fire for being overly simplistic. They commonly treated past climate changes as binary oppositions of "warm" ("low-ice") and "cool" ("high-ice") periods or of the long-term "advances" and "retreats" of the annual position of Arctic pack ice. They also failed to take into consideration internal social factors, such as the impact of human population growth, accumulation of technological knowledge and skills, exchange of technology, and so on. Later models of prehistoric human responses usually present the history of Arctic maritime cultures as a set of *adaptations*, that is, as active and deliberate adjustments to specific local environment(s) or certain environmental episodes. The environmental component is also presented today under a much more sophisticated framework. New factors, such as the formation of ice-leads and *polynyas* (Ackerman 1988, Anderson 1981, Mason and Gerlach 1995, Mason 1998, Schledermann 1980), the El Niño-La Niña system fluctuations (Mudar and Speaker 1999), long-term decrease (or increase) in storms and coastal erosion activity (Gerlach and Mason 1993, Mason and Ludwig 1990), and other variables are increasingly being incorporated by archaeologists into new environmental interpretations of culture changes.

<u>Late Historic/Modern Records</u>

There is no doubt that changes in Arctic climate and sea ice continued to exert a significant impact upon local economies and subsistence practices in Alaska and Siberia well into the late historic and modern period, that is, in the post-1850 era. However, the data to research such impacts are surprisingly scarce and at best inconclusive, as students of native culture change looked persistently at several other factors. The role of environmental fluctuations was indeed greatly obscured by the emergence of such new powerful agents of changes as the introduction of firearms and of other sophisticated equipment, such as whaling gear, outboard motors, and, later, snowmobiles. The rise of commercial markets for certain northern marine products, such as baleen, walrus ivory, and seal skins became a critical factor in shaping native hunting and in spurring native consumer demands for manufactured goods by 1870-1880. Shortly after, the once-thriving stocks of Pacific walrus and bowhead whale in the northern Bering and Chukchi Seas were almost annihilated by the commercial whaling industry (Bockstoce and Botkin 1982, 1983). This caused enormous hardship, population dispersion, social chaos, and mass starvation in coastal native communities in Alaska and Siberia alike (Bockstoce 1986).

Later transitions included: establishment of large permanent villages, introduction of wage economies, governmental modernization programs, and military construction booms that swept through native communities across the Arctic during the 1950s and the 1960s. This left few incentives for social scientists to consider climate and sea ice as major players in modern life in the North. Increased awareness of the potential implications of global climate changes in the early 1990s brought both new interest and advanced scientific techniques to the assessment of climate and sea ice variability and their effects in the Arctic regions. Needless to say, the key role of ice and weather regimes and of their variations and stability in the everyday life of northern communities was neither lost nor ever obscured to the Arctic residents themselves.

In fact, this process of reassessing research priorities within the scientific community is still unfolding; and this workshop may well become a milestone in shifting the balance as well as the focus of future efforts. Very limited scientific research has been done using modern (or late historic) data, and it is the most recent records that remain surprisingly incomplete. A few exceptions are worth mentioning. A long-term study of caribou stock health and management practices in Alaska and northern Canada is currently under way under a program hosted at the University of Alaska Fairbanks (Kruse *et al*. 1999). It is designed to produce an organized, multi-faceted record to match key shifts in environment, ice and weather regimes, and native management practices during the past century. Similar research projects have been already carried out for northern Scandinavia (Flanders *et al*., in press, Kurttila 1995).

With regard to coastal communities in the northern Bering Sea/Chukchi Sea region, existing data on subsistence hunting and fluctuations in the annual catches of key marine species offer a similarly insightful avenue for research. One recent study specifically targeted the links between sea ice distribution and historical fluctuations in native sea mammal catch records in the area of the northern Bering and southern Chukchi Seas (Krupnik and Bogoslovskaya 1998, 1999). The study used extensive Russian data on village sea-mammal harvests on the Chukchi Peninsula between 1935 and 1960 from local economic and catch reports of the time as well as other historical Russian sources.

The evaluation of historical hunting data by individual native communities and larger areas along the northern Bering Sea-Chukchi Sea coastline in Siberia revealed a fairly regular set of annual variations in the size and distribution of the native catch. As the study indicates, despite all the political and economic changes in Chukotka this century, these recurrent fluctuations in marine catches followed established patterns. Those patterns ("regimes") could be linked to annual weather and ice variations in the North Pacific/Bering Sea area, particularly to the varying spring position and later summer retreat and fall advance of seasonal pack ice. As elders recall and modern hunters learn from their everyday experience, both the high-ice and low-ice conditions off certain portions of the coast are clearly projected into the varying levels of hunting success. The availability of key marine mammals close to villages and the position of their migration routes (farther from or nearer to the shore) is always affected by the annual ice and weather regime. Ice and weather also affect the number of animals at the most productive sites, such as ice-leads, *polynyas*, and walrus shore- and ice-floe haulouts. Heavy ice, protracted strong winds, and storms can often prevent hunters from pursuing or even seeing the animals for days and weeks. This may be critical during the relatively short peaks of spring and fall migrations, when local hunters normally secure the bulk of their annual marine catch.

As modern-day hunters know and, as it was clearly presented during the workshop discussions, these environmental factors remain in place. They strongly influence the success or failure of every hunting season, often quite independently of the type of boats and other equipment used, of economic conditions, and/or current gasoline prices. Hence, the sea ice fluctuations caused by global climate change are of crucial importance to village economies. There is also an urgent need to organize and reassess existing data on Alaskan sea-mammal harvests from this perspective—by village as well as by key coastal regions. This may help to elucidate the role played by recent ice-weather fluctuations in several well-documented shifts in the productivity of local subsistence hunting for walruses, seals, and bowhead whales. For example, the annual walrus harvest in Gambell on St. Lawrence Island has increased from 200-300 during the 1950s to 300-500 in the 1970s, to 600-800 in the 1980s, to almost 1,500 in the most recent year of 1999.

Whether these changes in hunting productivity in Gambell as elsewhere in the region were caused by global warming and related changes in the sea ice regime, by advanced technology, by natural growth in the Pacific walrus population, or by increased hunting efforts and consumer demand remains unresolved. The main challenge here is to assess whether the Alaskan and Siberian sectors operate as a single unified Bering Strait ecosystem. If so, they would respond to similar environmental trends that could be illustrated by common analytical models for the entire northern Bering Sea-Chukchi Sea region.

<u>Responses to Change in the Past</u>

The available archaeological record of at least 3,500 years of continuous human occupation of the ice-covered Arctic coastlands provides ample evidence of successful adjustments of the local indigenous economies to past climate and ice changes. These data have been summarized in several recent studies that cover the Alaskan sector, Siberian sector, or both (e.g., Jordan 1989, Krupnik 1993, Minc 1986, Minc and Smith 1989).

Whereas students of past human responses to ice and climate changes in the Arctic may differ in specific interpretations, their main conclusions are surprisingly unanimous. They point out toward several successful adaptations that helped indigenous Arctic residents to cope with their highly unstable environment and to do it effectively, despite small population numbers and limited technological means. As Arctic technologies progressed, people tended to rely upon the ever-growing spectrum of marine and terrestrial game populations, to include eventually an amazing range of species and ecological settings (Krupnik 1993). Various marine and land resources have been exploited under complex and highly specialized local or seasonal patterns of rotation (the annual subsistence cycle). This successful pursuit of several and highly variable game species, both marine and terrestrial, was achieved thanks to outstanding knowledge about every aspect of the ecosystems that people exploited. In fact, this body of knowledge commonly went far beyond that which was essential for daily survival and basic subsistence activities; it always included data related to unusual circumstances and emergency conditions (Nelson 1969). Subsistence universalism was the rule and the knowledge about the environment was almost encyclopedic; nevertheless game resources with higher output and less risk per human effort were certainly most favored. Whenever local conditions permitted, people congregated in larger communities and they preferred to hunt by cooperative and well-organized groups (boat crews) and for larger prey, such as whales and walruses (Krupnik 1993).

Other studies indicate increased reliance upon stored food secured in the times of abundance as well as more active exchange, sharing, and cooperation among neighboring communities (Minc and Smith 1989). Population dispersion in small bands and/or hunting camps and opportunistic use of the variety of local environments off the most productive sites offered another valuable strategy in times of need (Jordan 1989). Last but not least was the impact of specific cultural practices, rituals, and taboos reflecting the numerous ethical and spiritual beliefs (Minc 1986, Minc and Smith 1989). This was an established *cultural framework* that regulated human interactions with game populations, including the amount of resources people extracted from their environment, how they did it, and how they acted in times of abundance as well as times of scarcity and need.

The strongest and most successful strategy of human response to climate change, however, has been the dynamic and highly flexible use of the environment, regardless of what people mostly hunted at particular times or locations. As Arctic residents experienced endless swings in local ecosystems and in the spectrum of subsistence resources available to them, they developed complex economic strategies, in which two or more resource use models developed in tandem (Krupnik 1993). By encouraging variability and cultural flexibility, Arctic people have created an economic continuum between more sedentary and more mobile subsistence models, and were always eager to embrace either one in response to change. As ice and sea, rivers and tundra, fishes, seabirds, caribou, and marine mammals fluctuated continually, they neither shifted all at once nor ever moved in one direction. Any changes in the environment augured poorly for certain parts of the subsistence spectrum but, by the same token, bolstered the range of alternative species, their usable biomass, and their productivity. When the ranges of pagophilic (ice-affiliated) marine species, such as walruses, ringed seals, and bowhead whales, moved further north, other species normally arrived in abundance, like salmon, harbor seals, or sea lions. When hunting became difficult off the open coast because of heavy ice or storms, other resources could be used elsewhere, such as caribou and domestic reindeer in the inland tundra or small seals in ice-bound inlets and bays. The aim of humans was thus to choose a more reliable resource base on the grounds of a costs-and-benefits approach, to initiate necessary adjustments, and to make this transition swiftly.

Both the short-term and long-term local strategies of coping with past climate changes have not lost their value in modern wage-oriented and commercially driven northern economies. The great majority of Arctic native people are still considered "rural residents" – about 70 percent in Alaska and 75 percent in Siberia. These numbers, though gradually shrinking, will not be altered significantly any time soon. Hunting for walrus and seals, communal whaling, land-game hunting, fur trapping, fishing, and family reindeer herding are critical occupations in many an Arctic community. They still play an enormous role in supporting native cultural continuity and ethnic identity, and in maintaining traditional practices and the customary diet.

Whereas many champions of modernization and economic globalization consider these subsistence activities obsolete and vulnerable, it is the industrial economy and big state programs that have been—as it has turned out—more vulnerable than village subsistence practices. Recent economic setbacks in the Russian Arctic forced many big industries to be downsized or totally abandoned. At the same time, this situation has pushed thousands of village and town residents back to their reliance on subsistence activities and local food. Despite their technological capabilities, modern economies and industries are, in fact, very poorly adapted to any environmental change in the Arctic (as elsewhere). They lack flexibility, rely on the continuous influx of outside resources, have low (if any) capacity of advance warning, and rarely if ever address the need for alternative or supplemental strategies for survival. Therefore, the record of past human responses and the knowledge of locally developed tactics for coping with environmental shifts remain critical in drafting any scenarios for modern adjustments to climate change.

Implications of Potential Changes

Several recent meetings and workshops as well as individual studies have focused on the impact(s) of future climate change and its potential implications for Arctic residents (Anderson and Weller 1996, Anonymous 1997, National Research Council 1996, Weller and Lange 1999). This issue is of the highest concern to Arctic residents and the scientific community alike. Several recent studies of future climate change are advancing models that feature a drastically shrinking area of polar sea ice or, in some cases, a totally ice-free Arctic, at least in summer. The implications of these new conditions for northern economies, local lifestyles, subsistence practices, and cultures of the Arctic people would indeed be enormous—if these projections ever are to become a reality.

Of the many potential impacts of future climate change upon local Arctic communities, the following have been identified as the most challenging (Weller and Lange 1999):

- changes in the availability of *key marine and terrestrial subsistence resources* at the strategic locations and times of the year; whales, walrus, seals, caribou, salmon and other fishes, and various species of waterfowl are likely to undergo shifts in range and abundance, due to altering weather and ice regimes;
- changes in *established harvest strategies* that most probably will require substantial reallocation of local labor, capital, and technology (like boats, snowmobiles, and weapons);

- transformation in main *food storage practices* as traditional means of food preservation via ground-cellar freezing, drying, etc., may be highly affected by increased temperature and shifts in summer precipitation;
- *accelerated permafrost thawing*, which will increase damage to and costs for existing building and pipeline maintenance, road and airstrip construction, sewage and waste facilities, public infrastructure, etc.;
- *unpredictability in supplemental and/or alternative resources* that are widely used by Arctic coastal residents; these include domestic reindeer herding, hunting for caribou and other inland game species, fur-trapping, plant gathering, etc.; inland resources are even more sensitive than coastal ones to shifts in temperatures and precipitation associated with changing sea ice regimes;
- *increased storm activity and coastal erosion*—this threatens many a coastal community and often requires village relocation and new construction at great expense;
- *increased risk of pollution and of new human and animal health problems*—as northern marine ecosystems may become more vulnerable due to warmer climate, less ice cover, and intensive water circulation; these factors may also trigger new diseases, as human and animal parasites move north.

While scientists and local residents alike advance their concerns about various potential impacts of the rapidly changing Arctic environment, there is a profound difference in the ways both parties address the very notion of change. Whereas scientists often view change as a short-term and rapid phenomenon, native residents usually see change as existential and they are more prepared to live with it (Weller and Lange 1999). This is quite understandable based upon the cultural and ecological experience of Arctic people, both modern and prehistoric. By the time any long-term Arctic resident approaches old age, he or she necessarily has memories of numerous events throughout the span of his or her personal environmental observations and experience. From this, people clearly gain increased sensitivity toward short-term and medium-term environmental shifts (Krupnik 1993)—whether those are changes in ice conditions, animal migration routes, or game abundance and availability at the usual places and times of year.

Certain cultural factors based on generational experience of living in the Arctic greatly enhance native adaptation to and the validity of native observation of the ongoing changes in Arctic ecosystems (as framed by Krupnik, in Weller and Lange 1999):

- "Being on the Land"—this facilitates continuous scanning of the environment for any signal of change and provides channels for advance warning. It also increases the role of strategies based on alternative resources in case of incoming environmental shifts.
- Reliance on long-term observations and generationally transmitted local knowledge about numerous components of the local ecosystem. This creates an enormous bank of local environmental observations and generalizations. It is culturally valuable and persistently maintained and transmitted within the community.
- "Always being ready"—a product of high mobility, economic flexibility, and an existential attitude to environmental change.

Maintaining diversified subsistence strategies—usually a combination of marine and land game hunting, fishing, herding, and trapping.

Therefore, the overall success of native responses to current environmental changes depends greatly upon the ability of native communities to match strategies derived from their traditional cultural experience (like subsistence flexibility, population mobility, increased use of alternative resources, etc.) with those provided by the modern economic and political framework. The ability to accommodate the data and recommendations derived from traditional (or tradition-based) knowledge and modern environmental science emerges as a key avenue for any future strategies of adaptation.

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BENTHIC PROCESSES IN THE NORTHERN BERING/CHUKCHI SEAS: STATUS AND GLOBAL CHANGE

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Introduction

The shallow Arctic waters have important pelagic and benthic foodwebs, with the benthos playing a much greater role in system production and turnover than at lower latitudes (Laevastu and Favorite 1981, Grebmeier and Barry 1992, Grebmeier *et al*. 1995). The Bering and Chukchi Seas contain some of the highest faunal biomass in the Arctic, as well as in the world ocean. High nutrient levels in the seawater are upwelled onto the shelf and influence the planktonic and benthic foodwebs as well as sediment community dynamics. In regions of high water column production there is a tight coupling between water column and benthic production. Both zooplankton grazing and the microbial loop have little influence on carbon utilization in waters that are extremely rich in phytoplankton, allowing more utilizable carbon to settle to the benthos to maintain a rich benthic food web. Regions of high benthic production in shallow Arctic seas, such as Lancaster Sound and the Bering, Chukchi, and Barents Seas support a large component of bottom-feeding fish, whales, seals, walruses, and seaducks (Hood and Calder 1981, Welch *et al*. 1992, Joiris *et al*. 1996).

Benthic production is extremely important in the northern Bering and Chukchi Seas, with high organic carbon deposition occurring over the shallow shelves, resulting in enhanced benthic standing stock to support key higher trophic organisms, such as Pacific walrus, gray whales, and bearded seals (Grebmeier *et al*. 1995). Predation by demersal fish, invertebrates, and marine mammals is an important factor limiting benthic biomass in the southeast Bering Sea. By comparison, cold temperatures limit fish populations in the northern Bering Sea northward, where benthic-feeding marine mammals and seabirds provide relatively higher regional predation pressure (Grebmeier *et al*. 1995). On the shallow Bering Sea shelf, the benthic food web is influenced by endotherm predation on bivalves and amphipods. The prey base for both gray whales and walruses is apparently declining as these apex predators approach or exceed carrying capacity (Lowry *et al*. 1980, Highsmith and Coyle 1992), so major environmental changes affecting prey communities are likely to have significant effects.

The Northern Bering and Chukchi Seas

The seasonally ice-covered Bering and Chukchi Sea shelves are some of the largest continental shelves in the world. Mean current flow of Pacific-derived water is northward over most of the year into the Arctic Ocean. Sea ice production, extent, and duration are critical for annual carbon production (both sea ice algae and open water phytoplankton), water mass formation, and hydrographic flow influencing subsequent carbon transport through the system, as well as resting sites for marine mammals. High primary production can occur regionally in the water column (up to 300 g C m^{-2} yr^{-1}; Springer and McRoy 1993, Springer *et al*. 1996), with ice-edge production quantitatively more important in regions of limited open water production. In specific areas of these seas this production is not directly consumed by pelagic secondary consumers, but rather by a rich macrobenthic community (Highsmith and Coyle 1992, Grebmeier 1993, Grebmeier and Cooper 1995). As a result, large populations of benthic-feeding marine mammals and birds serve as apex predators in the food chain (Fay *et al*. 1977, Grebmeier and Harrison 1992, Highsmith and Coyle 1992, Oliver and Slattery 1985, Oliver *et al*. 1983, Hunt 1991).

The benthos is a long-term integrator of overlying water column processes. The distribution of benthic standing stock (Figure 1) and sediment oxygen uptake (an indicator of carbon supply to the benthos; Figure 2) in the northern Bering and southern Chukchi Seas indicate a strong pelagic-benthic coupling of biological processes in the region (Grebmeier 1993, Grebmeier *et al*. 1995). The highest benthic biomass regions occur in the northern Bering Sea southwest of St. Lawrence Island, in the central Gulf of Anadyr, north and south of Bering Strait, at a few offshore sites in the East Siberian Sea, and in the northeast sector of the Chukchi Sea (Figure 1). By comparison, sediment oxygen uptake patterns indicate enhanced carbon deposition to the benthos southwest of St. Lawrence Island, northern Bering Sea, and southern Chukchi Sea (Figure 2). The lower uptake rates nearshore in the East Siberian and Chukchi Seas and northeast sector of the Chukchi Sea indicate reduced carbon deposition. This decoupling between benthic biomass (long-term scale) and sediment oxygen uptake (short-term scale) in these areas is likely due to higher current flow and associated transport of carbon past the sites on variable time scales.

Stable carbon and nitrogen isotope ratios of primary and secondary consumers in the northern Bering/Chukchi Seas also reflect the strong coupling between the pelagic and benthic components. In the Chukchi Sea, Dunton *et al*. (1989) found low ^{13}C enrichment of secondary consumers relative to that of zooplankton and similar ^{15}N enrichments among a variety of secondary consumers relative to zooplankton. These data reflect the existence of shorter food chains (Figure 3), which in the Chukchi Sea is related to a more direct coupling of benthic consumers to the very high pelagic primary production on the shallow shelf, little of which is grazed before reaching the sea bed (Dunton *et al*. 1989). Stable isotopic analyses of sediment organic carbon also indicate a coupling between the water column and benthos, with less negative ^{13}C values occurring under the more productive regions of the northern Bering and Chukchi Seas (Naidu *et al*., in press).

Geographically, the benthos in the region south of St. Lawrence Island and into the Gulf of Anadyr in the northern Bering Sea and the southern Chukchi Sea is dominated by bivalves, amphipods, and polychaetes (Grebmeier 1993, Grebmeier and Cooper 1994, 1995, Grebmeier *et al*. 1995). The area north of St. Lawrence Island to Bering Strait is dominated by amphipods and bivalves. As one moves northward to the Chukchi outer shelf the faunal are dominated by a mix of amphipods, bivalves, and polychaetes. Benthic faunal biomass declines northward in the Chukchi Sea, although there is an enrichment in benthic biomass near Barrow Canyon and the outer edge of the Chukchi continental shelf (Feder *et al*. 1994, Grebmeier, unpubl. data; Figure 2). A relatively rich region of benthic fauna also occurs just to the east in the Beaufort Sea (K. Dunton, unpubl. data). Observations of black, sulfide-rich muds near the head of Barrow Canyon suggest a shunting downslope of organic shelf-derived materials (Grebmeier and Cooper 1994, Devol *et al*. 1997). Ultimately, changes in the overlying flow directly impact benthic community structure, carbon deposition, and sediment composition. Sediment grain size is directly related to the current strength, and individual species of benthic infauna require specific sediment regimes within which to feed and grow.

The St. Lawrence Island Polynya (SLIP) Region

In the Bering Sea south of St. Lawrence Island (SLI), the water transport is predominantly from south to north. However, in the ice-covered winter/early spring period, the area is influenced by the seasonal SLI polynya (SLIP), an area of open water that develops south of SLI as prevailing northerly winds force sea ice away from wind-sheltering land-masses (Kozo *et al*. 1990). The SLIP extends 20-40 km (sometimes further) south over a shelf 30-70 m deep (Schumacher *et al*. 1983, Smith *et al*. 1990, Stringer and Groves 1991). This brine injection sets up periodic baroclinic currents that transport water and likely entrained organic matter to the south and then west as geostrophic balance is reached (Schumacher *et al*. 1983). Recent benthic studies indicate that the benthos underlying this cold pool area southwest of SLI has the highest oxygen uptake as well as benthic biomass on the northern Bering Sea shelf, suggesting that low temperatures do not limit benthic carbon cycling (Grebmeier *et al*. 1990, 1995). Very high standing stocks of benthic infauna (primarily bivalves) are maintained by nearshore primary production enhanced by SLIP dynamics, and subsequent baroclinic transport of carbon-rich waters southwestward from the island (Grebmeier 1992, Grebmeier and Cooper 1995). Total organic carbon content and C/N ratios of surface sediment also indicate deposition of high quality organic carbon southwest of St. Lawrence Island (Grebmeier and Cooper 1995).

Recent studies south of St. Lawrence Island suggest that changes in the bivalve populations over the last few decades are likely linked to changes in the northward transport of water across the shelf (Walsh *et al*. 1989, Grebmeier and Cooper 1995, unpubl. data, Roach *et al*. 1995). Benthic productivity is directly linked to higher trophic levels since the regional foodweb is dominated by marine mammal predation on bivalves and amphipods. The prey base for both gray whales and walruses is apparently declining as these apex predators approach or exceed carrying capacity (Lowry *et al*. 1980,

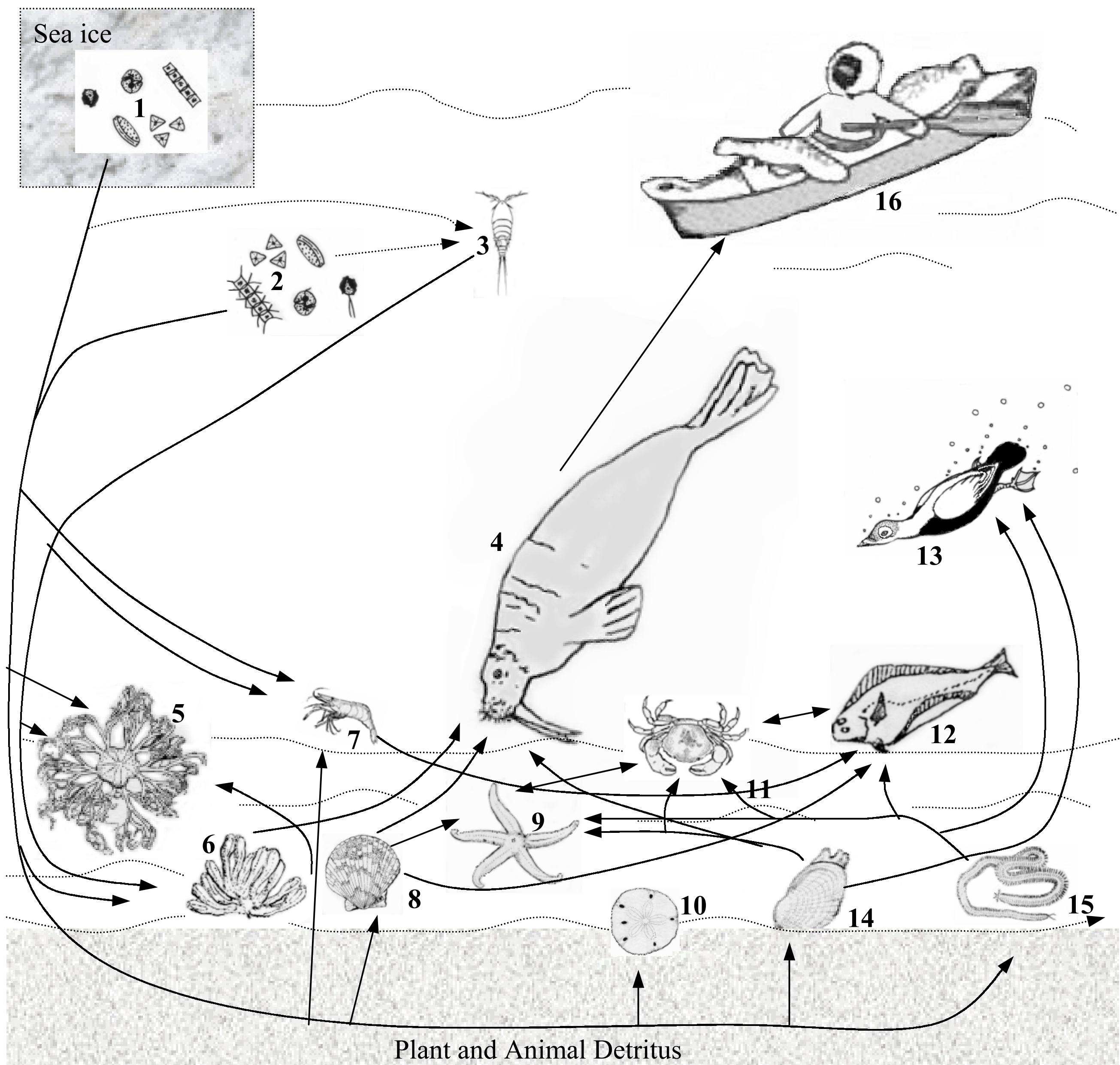

Figure 3. Representation of a simplified northern Bering/Chukchi Sea food web. The high density and abundance of benthic biota reflects the large proportion of phytoplankton that falls directly to the seabed, ungrazed by pelagic organisms. The direct assimilation of phytoplankton by the benthos results in shorter food chains and a more efficient transfer of carbon to large marine mammals and diving seabirds.

Organisms are: 1: ice algae; 2: phytoplankton; 3: copepods; 4: walrus; 5: basket stars; 6: ascidians; 7: shrimps; 8: filter-feeding bivalves; 9: sea stars; 10: sand dollars; 11: crabs; 12: bottom feeding fishes; 13: diving seabirds; 14: deposit feeding bivalves; 15: polychaetes, 16: native subsistence hunters.

Highsmith and Coyle 1992, Brendan Kelly, pers. comm.), so that environmental changes affecting prey communities are likely to have significant effects. In addition, the spectacled eider, a diving seaduck that winters under very harsh conditions in the Bering Sea (Petersen *et al*. 1995, Larned and Tiplady 1997), has been observed to dive for benthic food in sub-freezing water 40-60 m deep south of St. Lawrence Island. Ephemeral openings in the shifting pack ice are typically used. The wintering area was first located south of St. Lawrence Island in March 1995; up to 40,000 eiders from U.S. and Russian populations were packed together in single leads with bodies touching in water kept open only by movements of the eiders themselves (W. Larned, U.S. Fish & Wildl. Serv., pers. comm.).

Sediment oxygen uptake rates show a distinctive southwestern excursion away from SLI, implying an enhanced flux of particulate carbon to the benthos downstream from the SLIP (Figure 4a-c). However, a declining trend in sediment oxygen uptake in the productive areas to the southwest of SLI has recently been observed, with oxygen uptake decreasing from 35 mmol O_2 m^{-2} d^{-1} in 1988 to 20-25 mmol O_2 m^{-2} d^{-1} in 1993-1994 (Figure 4a-d). This decline in sediment oxygen uptake is indicative of a reduction of carbon supply to the benthos interannually. Multivariate community analyses indicate that there are different benthic communities to the southwest of the island relative to nearshore and much further offshore to the south and to the east (Figure 5a-c; Grebmeier and Cooper 1995 unpubl.data). Although benthic biomass fluctuates among years, there is also an indication of a declining trend in benthic biomass from 1990 to 1994 (Figure 5d; Grebmeier and Cooper, unpubl. data), and recent studies indicate this trend has continued in 1998 and 1999. This biomass decline coincides with indications since the late 1980s that benthic community structure has also been changing in the region (Sirenko and Koltun 1992).

Changes in Benthic Fauna and Oceanographic Processes

Recent retrospective studies of benthic communities indicate a changing marine system in the Bering and Chukchi Seas (Sirenko and Koltun 1992, Grebmeier and Cooper 1995, unpubl. data, Francis *et al*. 1996). In particular, the region just north of Bering Strait has historically been a settling basin for organic carbon, resulting in high benthic standing stock and oxygen uptake rates (Grebmeier *et al*. 1988, 1989, Grebmeier 1993). Specifically, the benthic productivity in a region north of Bering Strait near 67°30 N, 169° W has historically maintained the highest benthic faunal biomass of the entire Bering/Chukchi system (Stoker 1978, 1981, Grebmeier 1993, Grebmeier and Cooper 1994, Grebmeier *et al*. 1995, Reed 1998). Although benthic biomass remains high in the area, a change in dominant benthic fauna has occurred regionally and is likely an indication of changing hydrographic conditions (Grebmeier 1993, Grebmeier *et al*. 1995, Grebmeier, unpubl. data).

With respect to the St. Lawrence Island polynya region, any change in regional oceanography due to physical effects of the Gulf of Anadyr gyre position or size would ultimately be related to northward transport of water through Bering Strait, and

geostrophic balance within the Arctic Ocean basin. This balance drives the northward current regime in the northern Bering Sea (Walsh *et al*. 1989). Recently Roach *et al*. (1995) indicate reduced transfer of Pacific Ocean water north through Bering Strait, which suggests coincident reduction in northward transport of waters south of St. Lawrence Island. Water-column primary production and the final location of carbon deposition to the benthos is related to ice production and brine formation in the SLI polynya during late winter-early spring. The Gulf of Anadyr "cold pool" is maintained by ice production/brine formation in the SLIP. Reduced ice production south of SLI might decrease renewal of nutrients for early-season production by ice algae and phytoplankton, and baroclinic currents that would move it to the southwest (Grebmeier and Cooper 1995). Both these factors would limit benthic populations. Alternatively, an enhanced and more energetic polynya with global warming might maintain a chemostatic-type system as occurs north of St. Lawrence Island (Walsh *et al*. 1989), allowing a longer growing season with increased production and subsequent transport. On-going studies in the region are currently investigating a variety of these hypotheses (Grebmeier, Cooper, and Lovvorn, unpubl. data).

Current Regional Studies

There are a variety of ecosystem-type studies currently being undertaken in the northern Bering and Chukchi Seas, including work on long-term status and change of hydrography and benthic processes in the Bering Strait region (Cooperative Institute for Arctic Research /NOAA). Another collaborative program is investigating hydrographic forcing of benthic ecosystem change south of St. Lawrence Island (National Science Foundation [NSF]).

A new collaborative NSF and Office of Naval Research program was recently initiated called the Western Arctic Shelf-Basin Interactions (SBI) project that has as its goal to investigate and interpret global change impacts on biogeochemical cycling and trophic dynamics in the Chukchi and Beaufort Seas (Grebmeier *et al*. 1998; SBI home page: <http://utk-biogw.bio.utk.edu/SBI.nsf>). Sea ice extent and duration is a key element of the physical, biological, and geochemical aspects of this program and results from this current sea ice workshop will provide valuable insights for the objectives of the SBI program.

Also, an Environmental Observatory was recently funded by NSF to monitor the physical and biochemical parameters of waters that flow past Little Diomede Island in Bering Strait throughout the year (home page: <http://eco53.bio.utk.edu>). The program also includes annual oceanographic sampling of water column and benthic parameters at select high productivity sites south and north of Bering Strait. In addition, this observatory will rely on local Alaska Natives for many activities, such as collection of daily water samples at the land-based observatory and assistance with marine mammal and sea ice observations.

Summary and Future Research

The wide shelves of the northern Bering and Chukchi Seas support an extremely productive and dynamic benthic system. The high nutrient inflow of Pacific waters across these shelves supports high primary production that settles quickly to the underlying benthos. Both consumption by benthic organisms and benthic carbon cycling are extremely important for sequestering and recycling carbon over the shelves as well as supporting higher trophic levels utilized by local Inuit. These shelves are covered by sea ice for 6-9 months of the year and the role of sea ice in influencing the hydrographic structure in the region is critical for both water mass formation and carbon production and transport through the system.

Important questions for future studies related to sea ice and benthic systems include:

- What is the role of sea ice in ice algal community vs. open water production and how will changes in the extent and duration of the ice cover influence these processes?
- What is the interaction between ice extent and organic carbon flux to the benthos and how does the timing of ice melt interact with stimulating benthic production and carbon cycling?
- How will a projected reduction in ice thickness and extent influence the quantity and spatial location of organic carbon reaching the benthos?
- How will a reduced ice cover impact higher trophic level populations and their associated predation on the benthos?

An understanding of the interactions between sea ice formation and extent on water column and sediment carbon production and recycling processes is essential to predict the potential impact of global change on ecosystem dynamics in the seasonally-ice covered northern Bering and Chukchi Seas.

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THE ARCTIC SEA ICE ECOSYSTEM AND GLOBAL WARMING

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Introduction

The Arctic Ocean is a major component of the world's atmosphere-ocean system and within this ocean, sea ice is the dominant environmental feature. This several-meter-thick sea ice cover affects the magnitude of both heat and matter fluxes from the atmosphere and upper ocean and supports a unique and tightly coupled biological community – the Arctic sea ice ecosystem (Melnikov 1997).

A peculiar feature of the sea ice cover in the Arctic Ocean is the presence of permanent ice remaining after summer ice melting, as well as the seasonal ice that is formed on the surface of the Arctic Seas mainly in winter. The area of the sea ice cover at the time of its maximum development is formed by the areas of the deep Arctic Basin (4.47 million km^2) and areas of the shallow Arctic Seas (3.96 million km^2) for a total of 8.43 million km^2 (Gorshkov 1980). The annual cycle of sea ice formation, consolidation, and ablation is a fundamental process in the Arctic Ocean, significantly enhancing the degree of ecological variability as well as overall productivity (Legendre *et al*. 1992). Because sea ice is a physical layer dividing two environments different in thermal capacity – the atmospheric air and the ocean water – there is a sharp gradient between the environmental factors affecting its top and bottom surfaces. As a consequence of thermodynamic processes of melting and freezing, the ice continually modifies its thickness: growth from below during winter may be considered necessary to restore the ice layers lost as a result of summer melting. The sum of these processes and their seasonality is the homeostasis of the ecosystem supporting the equilibrium ice thickness (Zubov 1945).

Observations carried out in the early 1970s have shown that in spite of interannual variability in environmental factors, the time-scale characteristics, physical structure, chemical compounds, and species composition of the sea ice cover were stable within the vertical thickness of ice and within the geographical scale of the Arctic Ocean. These facts have allowed us to consider the sea ice cover as an integral and stable ecological system (Melnikov 1980, 1997).

Warming of the Arctic Ocean during the last decade is a phenomenon that has been the subject of wide discussion in the literature. Many general models predict a greenhouse-gas-induced warming in polar regions associated with a warming of the upper ocean and a substantial retreat of sea ice cover (*e.g*., Walsh 1991, McPhee *et al*. 1998, Johannessen *et al*. 1995, 1999, Vinnikov *et al*. 1999). As a physical layer between warm air and warm

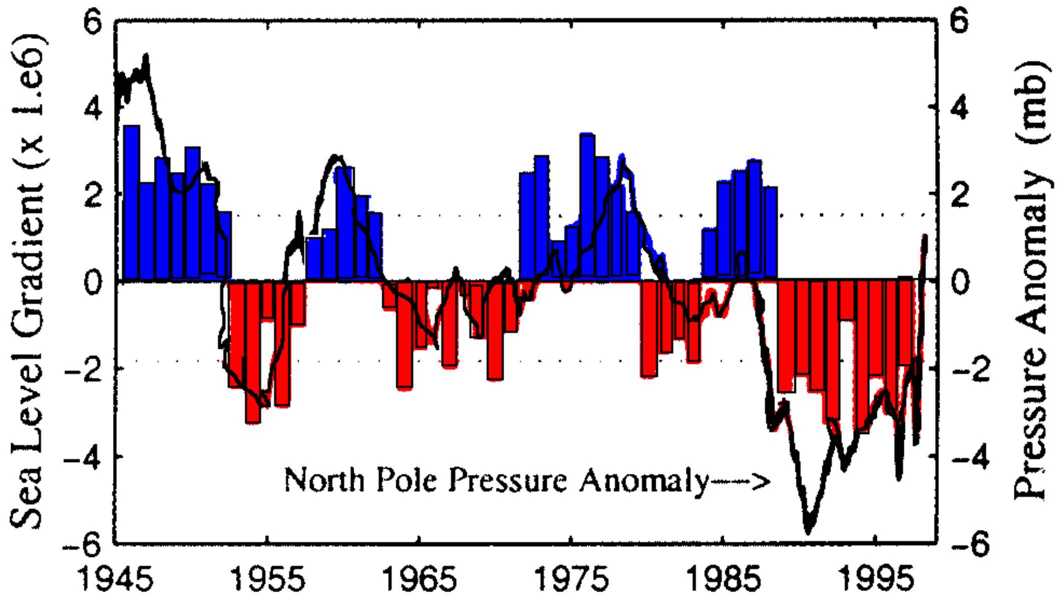

Figure 1. From 1946 to 1997, four anticyclonic and four cyclonic regimes track the Arctic Ocean oscillation. Recent SLP data suggest that the ocean-atmosphere system will shift to an anticyclonic state (Johnson *et al*. 1999).

upper ocean water, sea ice changes its thickness due to melting from both its top and bottom surfaces. Modern observations in the high Arctic have shown dramatic changes both in environmental factors and in the composition, structure, and dynamics of ice-associated biological communities in the Arctic Ocean. What changes do we really observe in the modern Arctic Ocean and how do these variations change the biological and geochemical characteristics of the sea ice cover?

From 1975-1981, the Soviet Ice Station "North Pole-22" (NP-22) drifted within the Beaufort Gyre in the Canadian Basin of the Arctic Ocean. From October 1997 to October 1998, the U.S. National Science Foundation conducted the round-year experiment SHEBA (**S**urface **HE**at **B**udget of the **A**rctic Ocean), supported by the Canadian Coast Guard icebreaker *Des Groseilliers* (Perovich *et al*. 1999). The drift of the Ice Station SHEBA was in the same area where the NP-22 had drifted two decades before. During the NP-22 and SHEBA drifts, multi-disciplinary studies of the sea ice/water system were carried out, including micro-scale sea ice observations and observations at the ice/water interface (Melnikov 1997, Sherr *et al*. in press). This workshop presents an opportunity to show preliminary data related to the questions of global change in the Arctic Ocean.

Changes in the Arctic Ocean

Ocean-atmosphere system oscillation

There is evidence that atmospheric circulation is changing, including a reduction in surface level pressure (SLP) over the Central Arctic Ocean. From 1946 to 1997, four anticyclonic and four cyclonic regimes track the SLP oscillation (Figure 1). Proshutinsky and Johnson (1997) identified anticyclonic wind-driven ice and surface water motion in the central Arctic for the periods 1946-1952, 1958-1962, 1972-1979, 1984-1988, and cyclonic motion for the periods 1953-1957, 1963-1971, 1980-1983, and 1989-1997. Recent SLP data suggest that the ocean-atmosphere system will again shift, or has already shifted, to an anticyclonic state (Johnson *et al*. 1999). The results of recent research on arctic climate oscillatory behavior show a standing SLP oscillation over much of the northern hemisphere associated with a sea ice anomaly propagating anticyclonic (clockwise) circulation around the Arctic Ocean (Mysak and Venegas 1998) and forcing upper ocean and ice circulation (Carmack *et al*. 1995, Morison *et al*. 1998) and river discharge (Johnson *et al*. 1999).

<u>Water masses</u>

Hydrographic data gathered during the last decade (icebreaker transects in 1990-1994, SCICEX cruises in 1993-1997) have supplied intriguing evidence that Atlantic Water flowing into the Arctic Ocean has warmed relative to previous years and has increased in volume by about 20% (Carmack *et al*. 1995, Morison *et al*. 1998). Warming relative to historical data was observed, as well as freshening of the upper ocean. A warm core of Atlantic Water with temperatures of 0.5^{o} to 1.7^{o}C was observed above the Lomonosov Ridge, and another less apparent warm core with a temperature of 1^{o}C existed over the Mendeleev Ridge. According to Carmack *et al*. (1995) and Morison *et al*. (1998), these data indicate a fundamental change in the circulation of the Arctic Ocean since the early 1990s. Changes were occurring at different depths and locations for different variables. Pacific Water transport since 1940 to 1998 also showed a remarkable trend in decreasing inflow through the Bering Strait (Coachman and Aagaard 1988).

<u>Ice extent</u>

Field and satellite-based observations show a rapid decrease in Arctic Ocean sea ice extent over the past 46 years (Cavalieri *et al*. 1999, Johannessen *et al*. 1999, Vinnikov *et al*. 1999). Satellite observations indicate a decrease in the area of ice extent of nearly 3% per decade since the late 1970s, accelerating in this decade (Cavalieri *et al*. 1999). Johannessen *et al*. (1995) reported a reduction of the annual mean ice cover of the Arctic Ocean between 1978 and 1994. Using satellite-derived ice maps, they estimated a decrease of the total sea ice extent of 0.05×10^{6} km^{2}/yr, of which 14% is due to a reduction of the area of multiyear ice. Reduction of sea ice cover is very noticeable in the Amerasian basin of the Arctic Ocean. Ten-year mean concentrations of the permanent sea ice cover following summer minimum ice area were remarkably lower and, conversely, the area of ice-free ocean (mainly in Chukchi and Beaufort Seas) was two to three times greater (Figure 2). As a reflection of the decrease in the surface area of permanent sea ice, the ice edge has migrated northward; e.g., the position of the ice edge in the Beaufort Sea in autumn 1998 was farther north than its historical mean autumn position (Figure 2).

<u>Ice thickness</u>

Rothrock *et al*. (1999) compared sea ice thickness data acquired by the Scientific Ice Expedition (SCICEX) in the mid-1990s with data from 1958 and 1976, finding a mean decrease of 1.3 m (around 40%) in ice thickness over the deep Arctic Ocean with greater

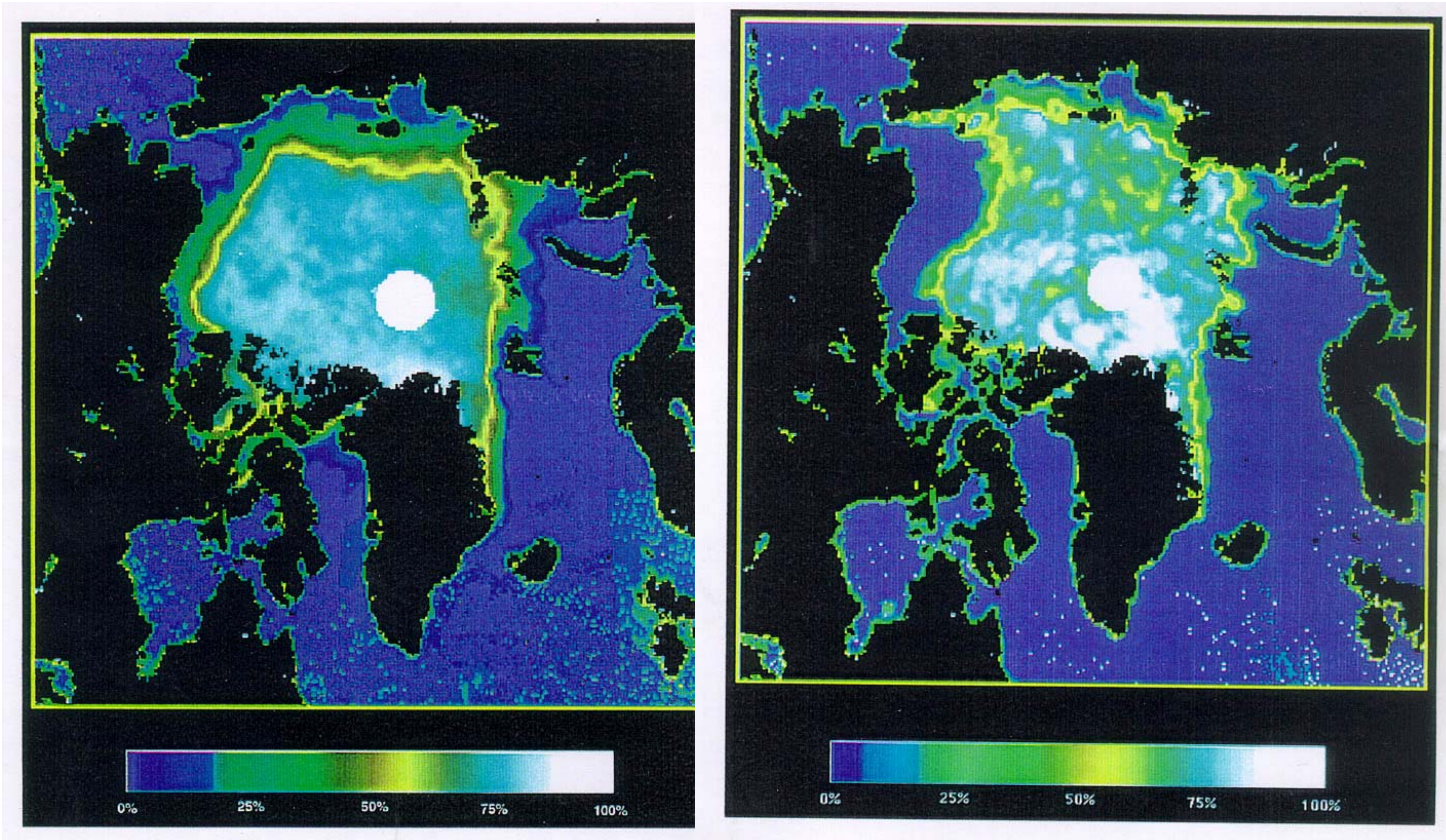

Figure 2. Ten-year mean concentrations of sea ice on September 30 as obtained from satellite passive microwave measurements (left) and sea ice concentrations on September 30, 1998 (right). Ice concentration ranges from 0% (blue) to 100% (white). SSMI digital images courtesy of W. Chapman, NASA National Snow and Ice Data Center.

decreases in the eastern and central Arctic than in the western Arctic. Data on reduced concentrations and thickness of perennial ice in different parts of the Arctic Ocean since 1970s were based on indications from submarine sonar. However, it remains unknown whether the nature of the perennial ice pack as a whole has changed. Perennial multiyear (MY) ice is approximately three times thicker than seasonal or first year (FY) ice, so that changes in ice type and distribution could both reflect and effect climate change in the Arctic Ocean. So, these data need to be supported by field studies to make time-series measurements of the thickness of all types of ice.

Mean sea ice thickness values of non-deformed and deformed MY ice from different geographical regions in the Arctic Ocean are shown in Table 1. Measurements were carried out directly during field observations at the "North Pole" ice drifting stations of the Soviet Union (Buzuev 1968) and during the transarctic crossing from Alaska to Fram Strait via the North Pole (Koerner 1973). Ice thickness ranged from 3 to 6 meters for the period 1967-1981. By 1997-98, ice thickness had dramatically decreased by 1.4-2.1 m in a region of the SHEBA drift in the Canadian Basin. This remarkable change can be explained by a decrease of cold-day temperature per year (i.e., the sum of daily average sub-zero temperatures at a given location) below the number needed to maintain the equilibrium thickness of ice at 3-6 meters. Since early 1970s, the sum of cold-day temperature decreased from 7000 (NP-22, 1974-1975) to 6200 (SHEBA, 1997-1998) for the same geographical region (Figure 3). Field observations during the SHEBA cruise (Cold Regions Research and Engineering Laboratory [CRREL] data) showed that

Ice thickness (cm)	**Type of Ice**	**Region**	**Year**	**Author**
334 **593**	*MY, non-deformed* *MY, deformed Deformed*	East-Siberian Sea	**1967**	Busuev (1968)
370 **430**	*MY, non-deformed* *MY, non-deformed*	Eurasian sub-basin Amerasian sub-basin	**1969**	Koerner (1973)
390-510	*MY*	Mean for the Arctic Ocean	**1981**	Wadhams (1981)
140-210	*MY, non-deformed*	Amerasian sub-basin	**1997-1998**	SHEBA,1997-1998 personal data

Table1. Mean sea ice thickness in the Arctic Ocean for the period 1970-1998.

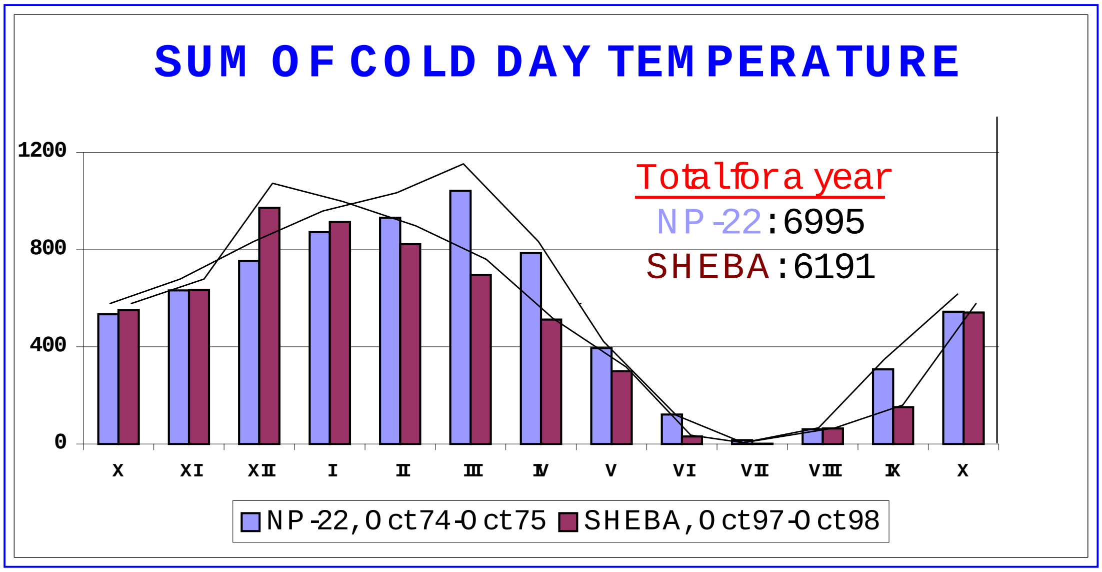

Figure 3. Sum of cold day temperature during the period October 1974-October 1975 (North Pole-22) and October 1997-October 1998 (SHEBA) in the region of the Beaufort Gyre (Canadian Basin of the Arctic Ocean). Within the same region, the cold day temperature period was longer in the early 1970s than in the late 1990s. The coldest month at NP-22 was March, but at the SHEBA Ice Camp it was December; in autumn (September), it was twice as warm during the SHEBA period than that of NP-22.

undeformed MY ice grew 75 cm during the winter, but lost 70 cm through surface ablation plus 40 cm through bottom ablation during the summer. Combining the growth and ablation gives a net thinning of 35 cm during the SHEBA year (Perovich *et al*. 1999).

Changes in the Sea Ice/Water Interface

Salinity/Temperature

Rapid melting of the sea ice cover during the last decade resulted in the freshening and warming of the upper ocean in the Arctic. McPhee *et al*. (1998) give CTD (conductivity-temperature-density) profiles for the upper 0-100 m obtained by the Arctic Ice Dynamics Joint Experiment (AIDJEX) (Oct 1975) and SHEBA (Oct 1997) expeditions in the same area (Figure 4). During this period of time, salinity values declined 3-4 parts per thousand in the 0-30 m layer and the temperature increased up to 0.4^{o}C. A distinct seasonal halocline was formed between 30 and 35 m, which was stable through the SHEBA winter up to April and formed a significant barrier to turbulent mixing, capping the remnant mixed layer. Between October 1997 and April 1998, the SHEBA station had traversed enough of the region to make it clear that the freshening was widespread.

Nutrients

The SHEBA mean annual values of Si concentrations (µg-at/l) per m^2 of the 0-30 m water column were about 60% lower during winter and about 40% lower in summer compared with the NP-22 data (Figure 5a).

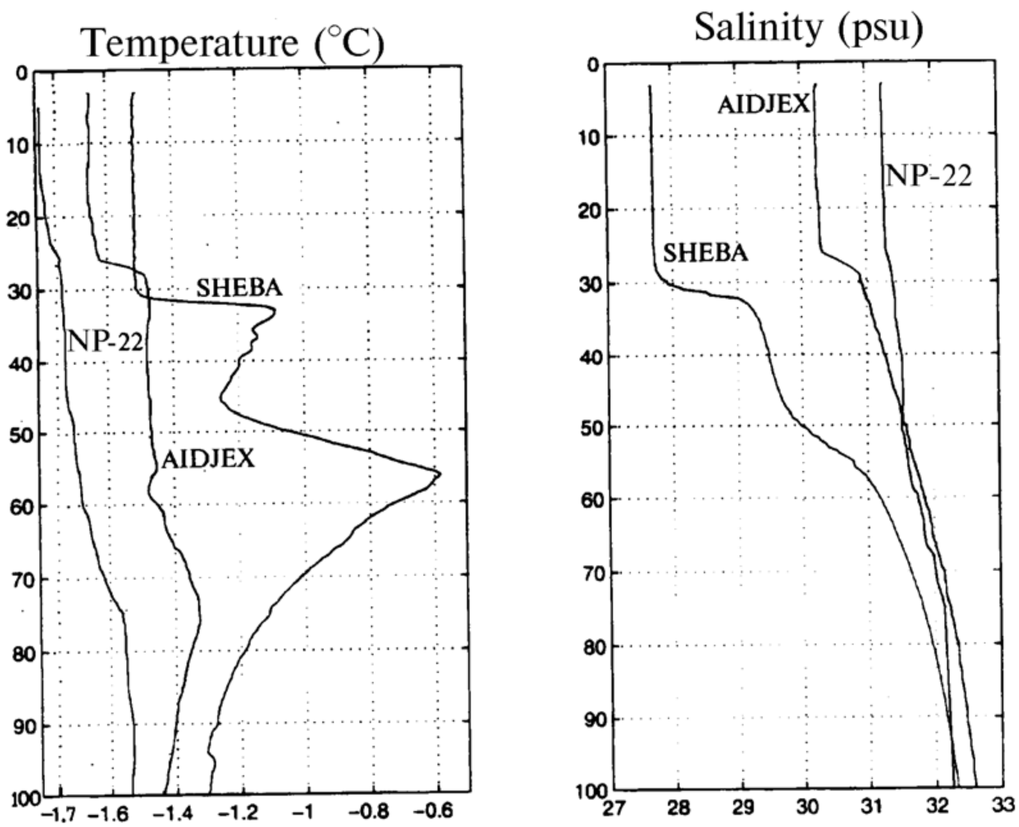

Figure 4. Temperature and salinity profiles from ice stations in the Beaufort Gyre: NP-22 (21 Oct 1975), AIDJEX (01 Oct 1975), and SHEBA (23 Oct 1997). Adapted from McPhee *et al*. (1998).

<u>Dissolved oxygen</u>

The SHEBA mean seasonal concentrations of O_2 within 0-30 m were 8% higher in the winter and 13% higher in the summer compared with NP-22 data. The NP-22 O_2 concentrations were seasonally stable, so that the summer-winter differences measured by SHEBA show a remarkable increase in seasonal variability (Figure 5b).

<u>Chlorophyll "a"</u>

The winter values from both SHEBA and NP-22 are similar but the summer concentrations for SHEBA were 55% higher than those of NP-22. In terms of chlorophyll, the annual standing stock during the SHEBA time was 0.273 μg/l, compared with 0.159 μg/l during NP-22. Increases in chlorophyll production (approximately 30%) may be explained by an activation of the phytoplankton photosynthesis beneath the sea ice that is, probably, connected with increasing of the dissolved oxygen concentrations in 0-30 m layer during the SHEBA time (Figure 5c).

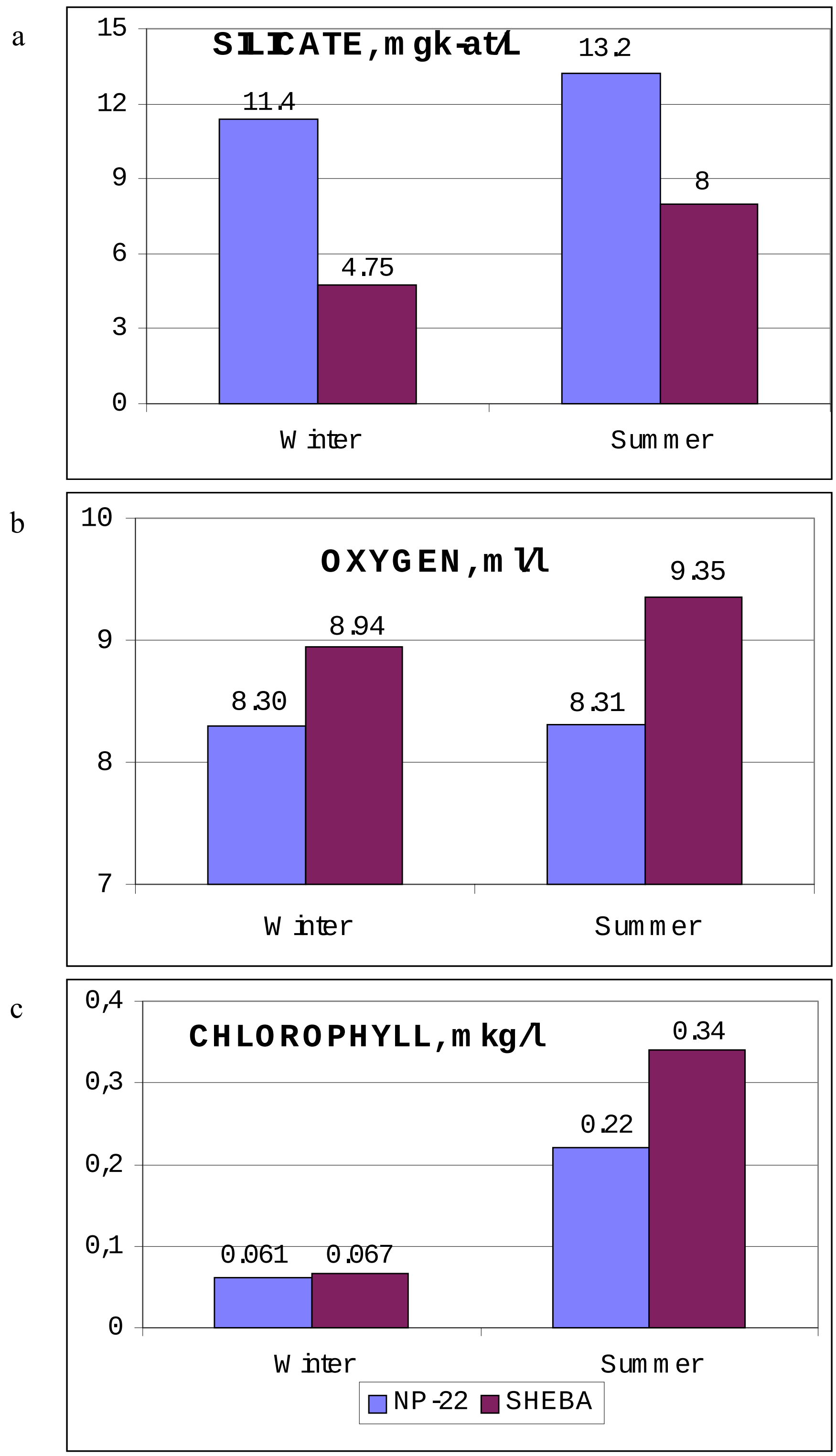

Fig. 5. Mean concentrations of silicate, oxygen, and chlorophyll_a in the 0-30m water column at NP-22 (1975-1976) and SHEBA (1997-1998).[FOR mgk USE µg]

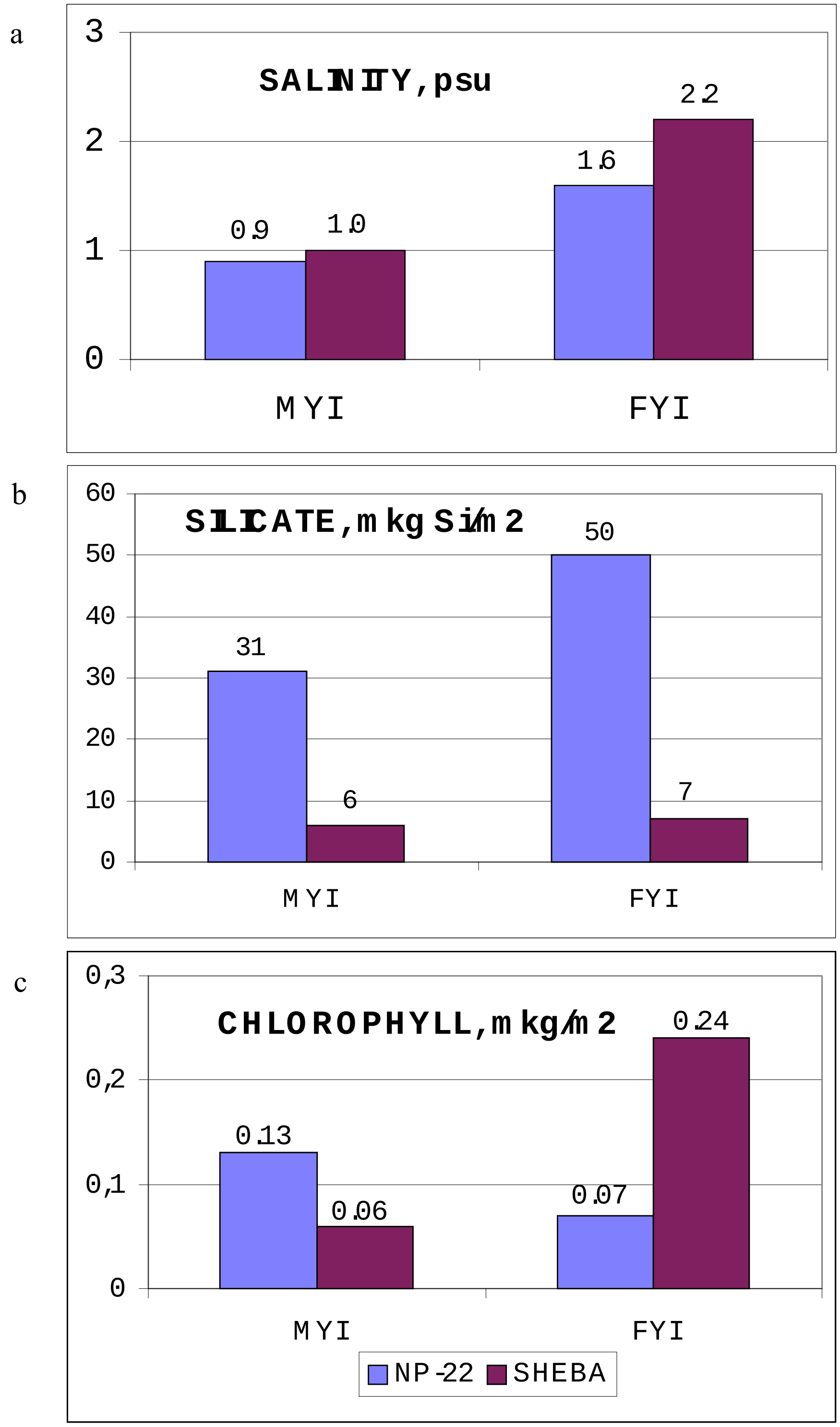

Figure 6. Mean salinity and concentrations of silicate and chlorophyll_a in multiyear (MY) and first-year (FY) ice at NP-22 (1975-1976) and SHEBA (1997-1998). [FOR mgk USE µg]

Changes within the Sea Ice Interior

Salinity
SHEBA and NP-22 mean salinity values of the multi-year (MY) ice are approximately equal (about 1 psu/m^2) (psu = salinity in parts per thousand) but SHEBA values of the first-year (FY) is higher of NP-22 salinity (2.2 psu/m^2 and 1.6 psu/m^2, respectively) (Figure 6a).

Silicate
The mean Si concentrations of both MY and FY ice from NP-22 are much higher than those from SHEBA. The most curious feature of the SHEBA ice samples is very low concentrations of Si in the MY and FY ice. Decrease of Si values within the sea ice interior may be caused by an active release of these components during the melting of ice, that, in turn, may limit the summer growth of sea ice diatoms (Figure 6b).

Chlorophyll "a"
The mean NP-22 chlorophyll concentrations in MY ice are twice as high as in samples from SHEBA (0.13 ug/m^2 and 0.06 ug/m^2, respectively) but the SHEBA values of the FY ice are 3 times higher than the FY values from NP-22 (0.24 ug/m^2 and 0.07 ug/m^2, respectively). The main feature of chlorophyll concentrations in the ice is a remarkable decrease of this component in MY ice in contrast to the large increase in the FY ice samples (Figure 6c).

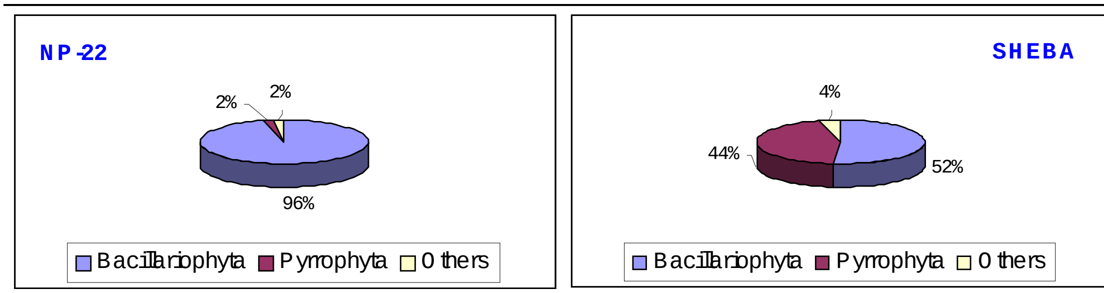

Figure 7. Sea ice flora associated with the sea ice/water interface at NP-22 (1975-1976) and at SHEBA (1997-1998).

Changes in the Sea Ice Biota

I. Sea ice/water interface

Flora
Eighty-five species were identified in samples collected at the NP-22 and SHEBA stations from the bottom surface of the ice. These species can be broken down in the following categories for the NP-22 and SHEBA sites respectively: Bacillariophyta – 46 and 22; Pyrrophyta – 1 and 19; Others – 1 and 2 (Melnikov *et al*. 2000). The main features of the SHEBA and NP-22 algal populations associated with the bottom surface of ice are:

1. A remarkable decrease of diatom species from 46 species or 96% of algal populations (NP-22) to 22 species or 52 % (SHEBA) in the under-ice layer (Figure 7);
2. Remarkable differences in species composition between the under-ice phytoplankton of SHEBA and NP-22: only 3 species from diatoms (*Chaetoceros socialis, Cylindrotheca closterium, Thalassionema nitzschioides*), 1 dinoflagelate (*Dinophysis acuta*), and 1 silicoflagelate (*Dictyocha speculum var. octonarius*) were common for both algal communities; the overall similarity between species from the SHEBA and NP-22 algal populations was only 8%;
3. A remarkable increase of Pyrrophyta in the SHEBA samples (19 species) compared with the NP-22 (only 1); and
4. The development within the ice/water interface at the SHEBA station of large aggregations formed by the fresh-water algae *Ulothrix implexa* (Kutz), which is a very common species in brackish waters but which had never been found before in the high marine Arctic.

Fauna

The total list includes 59 species. Of the 43 species in the NP-22 collection and 37 species from SHEBA, only 21 species were in common, or 37% of the total list (Melnikov *et al*. 2000). The main difference is due to amphipods: 14 species or 33% of total populations in NP-22 and 4 species or 11% of total populations in the SHEBA collection (Figure 8). Dominant species of the cryopelagic fauna in the NP-22 collection, such as polychaetes *Antinoella sarsi* and mysids *Mysis polaris*, were not observed by SHEBA. At the same time, in SHEBA water, the role of jelly-like plankton such as appendicularians, medusas, and benthic larvae are remarkably increased compared with NP-22.

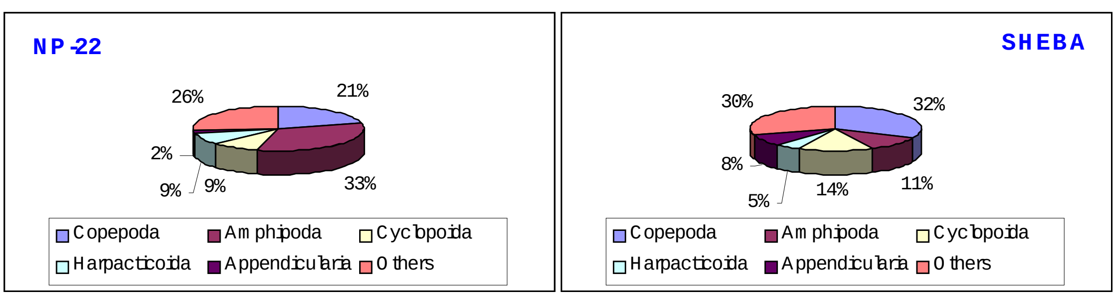

Fig. 8. Sea ice fauna associated with the sea ice/water interface at NP-22 (1975-1976) and at SHEBA (1997-1998).

II. Sea ice interior

Flora
The total list of sea ice algal populations includes 102 taxa; 84 species or 76% of the total list were indicated in NP-22, whereas in SHEBA they were only 26 species or 23%, respectively (Table 2). Species similarity between the NP-22 and SHEBA was only 8%.

NP-22 1979-1980	**Interstitial Flora**	SHEBA 1997-1998
79	***Bacillariophyta***	18
0	Pyrrophyta	5
0	Chrysophyta	1
0	Silicoflagellatae	1
5	Chlorophyta	1
Total: 84	**Total species number: 102**	Total: 26
	Similarities between species: 8%	

Table 2. Sea ice flora associated with the sea ice interior at NP-22 (1979) and at SHEBA (1997-1998).

The prevalence of diatoms is most variable in both MY and FY ice at the NP-22 (79 species) compared with SHEBA (18 species). Fresh water algae (mostly *Chlorophyta*) were detected only on the upper surface of ice. The obvious predominance of fresh water algae compared with diatoms is the main peculiarity of the algae populations from SHEBA: fresh water algae (*Pyrrophita*) were dominant by number and were distributed within both the MY and FY ice interior from the snow-ice surface to the sea ice/water interface.

Fauna
The main intriguing feature of the MY and FY sea ice faunal populations is an absence of interstitial fauna within the sea ice interior in the SHEBA ice samples; these fauna had previously been detected in high numbers in the NP-22 samples. In contrast to the nine species detected in NP-22 including *Protozoa, Foraminifera, Acarina, Nematoda, Turbellaria, Harpacticoida*, and *Amphipoda*, ice samples from SHEBA held only one specimen of *Foraminifera* (Table 3). The free-living nematode *Theristus melnikovi* associated with the sea ice interior was very common in the ice samples from NP-22, but was never been detected in the sea ice samples from SHEBA.

NP-22 1979-1980	**Interstitial Fauna**	SHEBA 1997-1998
3	Protozoa	0
1	Foraminifera	1
1	Acarina	0
2	Nematoda	0
1	Turbellaria	0
1	Harpacticoida	0
1	Amphipoda	0
Total: 10	**Total species number: 10**	Total: 1
	Similarities between species: 10%	

Table 3. Sea ice fauna associated with the sea ice interior at NP-22 (1979) and at SHEBA (1997-1998).

Implications for Future Climate Change

Thus, observations over the last two decades (SHEBA versus NP-22) confirm dramatic changes due to a warmer climate within the sea ice biological communities in the Central Arctic Ocean:

- SHEBA populations of sea ice diatoms are very scarce by species and number both in the multi-year and in the newly formed ice;
- freshwater green algae previously developed on the upper-ice surface and/or within the upper sea ice layers (NP-22) are now dominant by number and are distributed through the whole thickness of sea ice (SHEBA);
- populations of invertebrate animals like nematodes, copepods, amphipods, and turbellarians that previously lived in the sea ice interior (NP-22) were not found in the multi-year ice and newly formed sea ice (SHEBA); and
- in the SHEBA samples, cryopelagic fauna associated with the bottom sea ice surface as well as the under-ice zooplankton were scarce by species and numbers.

Observed changes in the composition and structure of sea ice biological communities may be explained by the growing melting of the sea ice cover during the last decade. Several factors likely to have been responsible include: (1) drainage of fresh water throughout the sea ice interior, (2) accumulation of fresh water beneath the ice, and (3) formation of the sharp halocline at around 30 m. The recent water/ice system above the halocline may, in fact, be more a freshwater/brackish system than the real marine system. On this basis, it seems that dramatic changes within the sea ice environment can be considered a result of global warming in the Arctic.

Recent scientific meetings and workshops have focused on the impact of future climate change and its potential implications for Arctic indigenous populations (Weller and Lange 1999). Many issues are of the highest concern to both Arctic residents and the Arctic scientific community. What are the potential effects on high Arctic nature due to a drastically shrinking area of polar pack ice, an increase of the seasonal sea ice surface, or a totally ice-free Arctic Ocean, at least in the summer? How will these changes impact the economics, lifestyle, and culture of Arctic residents as well as the political and economic framework of the circumpolar Arctic countries? All these issues are of great concern and urgently need to be discussed and studied.

On the basis of the historical materials and recent observations obtained over the Central Arctic Ocean, it may be concluded and speculated that:

- the modern *permanent sea-ice cover* in the Central Arctic Ocean has rapidly decreased both in surface area and in thickness, and the ice-edge has moved significantly farther north;
- both the *ice-free water surface* and *seasonal sea ice* have increased remarkably, especially in the areas of the Chukchi and Beaufort Seas;
- sea-ice cover of the Arctic Ocean will become more similar in its characteristics to the Southern Ocean, where seasonal rather than permanent sea ice is a dominant component of the marine ecosystem;
- the increase of *seasonal sea ice* versus *pack ice* and the advance of *ice-free areas* will promote photosynthetic activity of phytoplankton within the water column due to strong penetration of light, and ice-associated primary production will be reduced compared with that of the water-column.

From the early 1930s, it has been well known that the ice edge is the area of highest biological production in the ice-covered arctic seas (Usachev 1935, Shirshov 1937, Zubov 1945). The recently observed shrinking of the permanent sea-ice cover in the Arctic may be considered a signal for a strong northward shift of ice-associated animals including birds and marine mammals as the ice-edge retreats. If this scenario is more or less probable, can we speculate that recent observations of beluga whale migration far to north depends on this ice-edge retreat and the degeneration of the quality of pack ice in the Arctic Basin (L. Lowry, Alaska Department of Fish and Game, personal communication, 2000)? If so, the sea-ice-dependent lifestyle of Arctic indigenous people will be sharply changed in the near future. To understand this phenomenon, we urgently need long-term and large-scale observations of sea-ice-associated processes over the whole Arctic.

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CLIMATE CHANGE AND MARINE ECOSYSTEMS OF THE WESTERN ARCTIC

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The most widely known consequence in Arctic seas of climate warming in this century has been the loss of sea ice. In recent years seasonal ice extent and the thickness of the ice have both decreased**.** The loss of sea ice has many implications for Arctic ecosystems, the animals that live there, and the people who depend on those resources for their lives and lifestyles.

Perhaps the most obvious deleterious change is the reduction in essential habitat for several species of marine mammals. Polar bears, walruses, bearded seals, and ringed seals rely on sea ice as a substrate on which to haul out and, for some, to den. The extreme retreat of sea ice beyond the continental shelf of the northern Chukchi and Beaufort seas in recent years may have stressed walruses, for example, by maintaining them at a distance from feeding areas in shallower water over the shelf.

The food web associated with sea ice is critically important to populations of several species of marine mammals and seabirds. An under-ice community is supported at its base by epontic algae, those that live at the ice-water interface (Horner 1985). A variety of crustaceans graze the algae, and in turn are preyed upon by Arctic cod, the single-most important species of forage fish in the Arctic (Andriashev 1954, Bradstreet *et al*. 1986, Welch *et al*. 1992). Ringed seals and beluga whales in the Arctic depend on Arctic cod (Lowry *et al*. 1980, Welch *et al*. 1992), as do seabirds including thick-billed and common murres, black guillemots, black-legged kittiwakes, and ivory gulls (Divoky 1976, Bradstreet 1980, Springer *et al*. 1984).

Although Arctic cod are found in open water away from sea ice in summer in the Chukchi and Beaufort seas, it nevertheless is a cold-water species, preferring temperatures characteristic of Arctic habitats (Andriashev 1954, Craig *et al*. 1982, Gillispie *et al*. 1997). The distribution of Arctic cod in summer in the Bering Sea is determined by water temperature: it is much more abundant and wide-spread in years of heavy sea ice and the development of an extensive cold pool on the eastern shelf (Wyllie-Echeverria and Wooster 1998). If temperatures continue to warm, the range of Arctic cod may retract northward, limiting their availability to dependent predators. A possible analog of such a process has been recently suggested in the northeast Atlantic. There is speculation that Atlantic cod, a cold-water species, is being displaced northward by continued warming of the north Atlantic, jeopardizing the commercial fishery (Pearce 1999).

Many of the anticipated effects of climate change on Arctic ecosystems and key components—sea ice and marine mammals and birds—are negative. There may be compensating positive effects, however, that will in certain cases mitigate some of the negative ones. For example, in the coastal zone of the northeastern Bering Sea and eastern Chukchi Sea, early warming in spring and warmer summer water temperatures favor the productivity of the neritic community found in that habitat (Neimark 1979, Springer *et al*. 1984, Springer *et al*. 1987). Early retreat of sea ice from Norton Sound and break-up of the Yukon River enhance warming of the regional environment and advance the development of Alaskan Coastal Water (Coachman et al. 1975), a coastal jet originating on the southeastern shelf of the Bering Sea and flowing north through eastern Bering Strait (Figure 1). It constitutes approximately a third to a half of the total flow through Bering Strait, and contrasts in many ways with Anadyr Water, the other major source of flow through Bering Strait in the west. Alaskan Coastal Water has a low salinity, is nutrient-poor, and in summer is warm, compared to high-salinity, cold, nutrient-rich Anadyr Water. Both water masses play crucial roles in ecosystems of the Bering-Chukchi shelf.

Alaskan Coastal Water transforms the coastal eastern Chukchi Sea into a more productive and diverse ecosystem than is typical for such high-latitude seas by advecting heat and planktonic biota, and providing a conduit for mobile boreal fauna into the otherwise cold Arctic. Species that apparently benefit include sand lance, saffron cod, herring, salmon, and their predators—marine mammals, seabirds, and humans. For example, seabirds nesting in the eastern Chukchi enjoy much higher productivity in warm-water summers than in cold-water summers (Springer *et al*. 1984). The main difference appears to be related to the abundance and diversity of forage fishes. In any year, the birds rely on Arctic cod in spring and early summer when seasonal sea ice is present. In cold years, Arctic cod remains the principal prey throughout most of summer, but it is not sufficiently abundant, available, or nutritious to satisfy the needs of some species of seabirds to produce large numbers of chicks. In warm summers, however, boreal species of forage fishes arrive in time to provide the needed supplement to Arctic cod, and seabird productivity is typically high. Such differences in forage fish diversity and abundance could be of consequence to piscivorous marine mammals as well. Theoretically, then, warming in the western Arctic could favor the productivity of a boreal neritic community that includes species of forage fishes of importance to a variety of marine birds and mammals.

Additional evidence that a warm Arctic is not necessarily bad is found in the population dynamics of murres at Cape Lisburne. Cape Lisburne is the site of the northernmost, and one of the largest, colonies of murres in Alaska. The colony was first censused in 1977, and since that time the abundance of murres has grown steadily until there are now twice the original number (D. Roseneau unpubl. data). The rate of increase can easily be accounted for by productivity alone or by juvenile or adult survival, suggesting that environmental conditions during the last, generally warm, 25 years in the Chukchi Sea have been good for the population, and by extension, apparently good for the food web of which several species of marine mammals are a part.

In addition to recent changes in sea ice, there has been another oceanographic change in the Western Arctic that may have important consequences on ecosystem productivity.

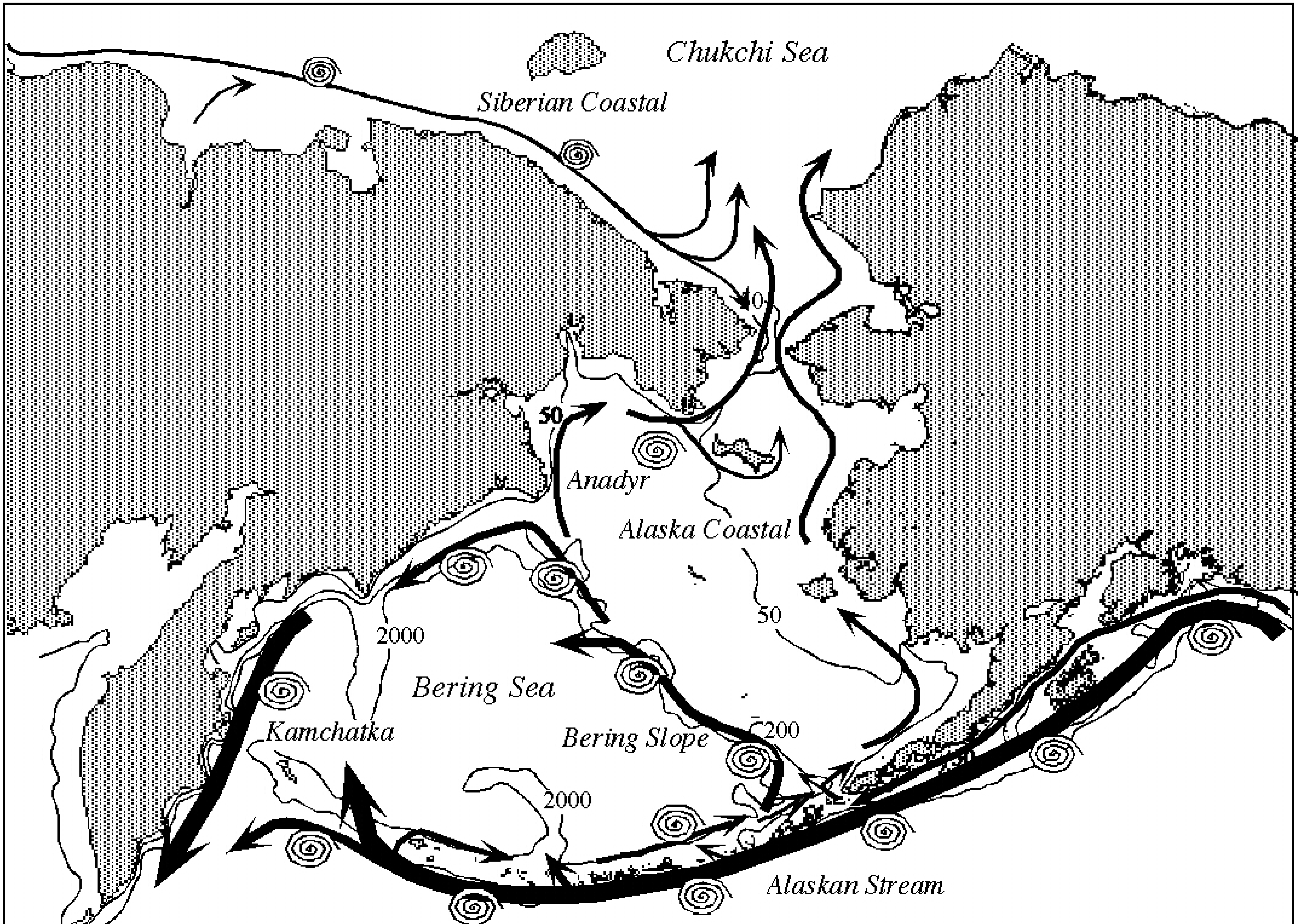

Figure 1. Generalized major currents in the Bering Sea and southern Chukchi Sea

Transport of water northward through Bering Strait has declined by approximately 30% since records were first kept in the early 1940s (Coachman and Aagaard 1988, Roach *et al*. 1995, T. Weingartner unpubl. data). The significance of this may be expressed in annual production budgets through declines in primary production, the advective transport of zooplankton, and alterations to the physical habitat.

The annual production cycle in northern seas typically consists of a spring bloom in April-May when the bulk of the primary production occurs. The bloom ends when nutrients, primarily nitrate, are depleted from the euphotic zone. In shallow water less than about 50 m deep, nitrate is depleted from the entire water column, while over the remainder of the continental shelf nitrate depletion occurs only in the upper mixed layer, above the seasonal thermocline. In these deeper waters, additional post-bloom production depends primarily on the strength of summer storms that can break down the stratified upper layer and mix nutrients from depth up into the euphotic zone. Annual primary productivity over most of the continental shelf of the Bering Sea ranges between about 50-150 g C m^{-2} y^{-1}, and only about 30-50 g C m^{-2} y^{-1} on much of the shelf of the Chukchi Sea (Figure 2).

In contrast, annual primary productivity across the shallow shelf of the northern Bering and southern Chukchi is in the range of 300-600 g C m^{-2} y^{-1} (Sambrotto *et al*. 1984, Springer and McRoy 1993). Daily production rates are of world record proportion (McRoy *et al*. 1987). Such prodigious productivity results from the flow of water northward through Bering Strait. Approximately half of the total transport consists of Anadyr Water, a water mass that originates at depth along the edge of the continental shelf in the northwestern Bering Sea. The basin of the Bering Sea constitutes an immense reservoir of nutrients (nitrate, phosphate, silicate) essential for the growth of phytoplankton. Concentrations of these nutrients in the deep Bering Sea are the highest in the world outside of eutrophic coastal regions receiving runoff from cities and farms. These nutrients are carried in the flow of oceanic water—the Anadyr Stream, literally a river in the sea—through the western Bering Strait region, where they provide an endless supply to phytoplankton. Primary production is proportional to nutrient supply rates (*i.e.*, volume transport of the Anadyr Stream) which vary among years (Springer and McRoy 1993).

The immense production of phytoplankton in the region is responsible for a highly prolific benthic food web that includes ampeliscid amphipods and bivalves and their predators, gray whales and walruses (Grebmeier *et al*. 1988, Fay 1982, Nerini 1984). It is safe to say that were it not for the Anadyr Stream, populations of gray whales and walruses in the northern Bering and southern Chukchi would be much smaller than they are today.

In addition to nutrients, the Anadyr Stream carries an immense amount of oceanic zooplankton through the region—on the order of a million tonnes per year (Springer *et al*. 1989). The majority consists of species of euphausiids and large calanoid copepods that are the main link in pelagic food webs between phytoplankton and planktivorous vertebrates such as many seabirds and whales. Thus, in the nesting season, St. Lawrence

Island, King Island, and the Diomede Islands host millions of least and crested auklets that have been an important element in the subsistence economies of human residents of these islands for millennia. Moreover, piscivorous seabirds, such as murres and kittiwakes, which also are important subsistence resources, are abundant and diverse in the region because of forage fish populations—capelin, sand lance, Arctic cod— that flourish on the rich zooplankton (Springer *et al*. 1987). This larger marine region is the wintering area, and was formerly the summering area as well, for bowhead whales (Bockstoce and Botkin 1983, Springer and Roseneau 1985).

And today, the bowheads are telling a story about changing oceanography in the western Arctic (Schell 2000). Recorded in their baleen are chemical signatures of food web structure and productivity in the form of stable isotopes of carbon and nitrogen. The most intriguing aspect of the information compiled from whales over many years is a long-term change in the ratios of carbon isotopes that can be interpreted as reflecting a decline in primary productivity. The degree of the decline is approximately 30% in the past 30-40 years. The similarity between this value and the decline in transport may be coincidental, but a cause-and-effect relationship seems plausible, based on the relationship between productivity and transport found in field studies (Springer and McRoy 1993). If this is the correct interpretation of the baleen isotope data, it indicates that the carrying capacity of the ecosystem of the Bering-Chukchi shelf has declined by about 30%, since primary productivity sets the upper limit on biomass yield at all higher trophic levels.

A lack of information on other parts of the system hampers our understanding of the validity and significance of this argument. For example, have there been trends in benthic production during this time? Benthic communities owe their abundance to the overlying primary production. In spite of their huge biomass, zooplankton cannot control the persistent phytoplankton bloom and most of the cells settle to the bottom, fueling the prolific growth of invertebrates that feed gray whales and walruses. If transport and primary productivity have declined by 30%, this could lead to a similar decline in overall food web production, providing an alternate hypothesis to explain the recent low body condition of walruses in northern Alaska.

Declining volume transport of Anadyr Water would also reduce the advective supply rate of zooplankton to the Bering-Chukchi shelf. This in turn could have some negative effect on bowhead whales, the vast populations of auklets, and several species of forage fishes and their predators in the region.

The cause of declining transport is not known. The flow is maintained by a north-south atmospheric pressure differential that effectively tilts sea level down toward the north (Coachman *et al*. 1975). A changing balance in this differential is the likely cause of declining transport, but how that relates to trends and oscillations in weather and climate is a puzzle.

Identifying the causes and time scales of fluctuations in the physical environment, such as in meteorology and sea surface temperature, is a challenge that must be met in order to understand ecosystem responses and predict the direction and significance of future changes. For example, a decadal-scale oscillation in meteorological conditions over the North Pacific has been identified recently and is now known as the Pacific Decadal Oscillation, or PDO (Trenberth and Hurrell 1994, Mantua *et al*. 1997). For reasons not well understood, the Aleutian Low, the dominant meteorological feature over the North Pacific, alternates between two quasi-stable states of strength and location. Each regime, or the time a given state persists, varies in duration of about 1-2 decades before shifting abruptly to the alternate state. This oscillation has been evident since the beginning of this century, when pressure data were first recorded.

Physical correlates to the PDO include a teleconnection to the El Niño-Southern Oscillation in the central Pacific; interactions with the Siberian High pressure system, a prominent meteorological feature also affecting the western Arctic; and sea ice cover in the Bering and Chukchi seas (Niebauer 1998). The relationship of the PDO to sea ice cover adds uncertainty about the significance and expected persistence of recent trends. That is, an abrupt decrease of over 5% in ice coverage occurred after a regime shift in 1976. This raises the question of which has been more important in the sea ice budget of the western Arctic in recent years—global climate warming, or the PDO? If it is the former, sea ice should continue to decrease. If it is the latter, we would expect a return to heavier ice conditions with the next regime shift, which could occur at any time.

Besides physical correlates to the PDO, there are many biological ones too. This was first pointed out by Ebbesmeyer *et al*. (1991) for a variety of environmental changes related to the 1976 regime shift. Since then, numerous other associations have been identified, including ones between the PDO and the productivity of phytoplankton, zooplankton, Pacific salmon, forage fishes, seabirds, and marine mammals (Francis and Hare 1994, Polovina *et al*. 1995, Brodeur *et al*. 1996, Piatt and Anderson 1996, Anderson *et al*. 1997, Springer 1998). The relationship between ecosystem productivity and the meteorological state over the N. Pacific complicates attempts to understand the significance of longer-term changes in the environment, such as global warming.

Likewise, superimposed on the long-term warming trend in the Arctic is a decadal-scale oscillation in sea water temperature (Royer 1993, Springer 1998). In the Bering and Chukchi seas, water temperature has numerous biological correlates, including patterns of seabird productivity, growth rates and recruitment of forage fishes, and development of zooplankton populations (Neimark 1979, Springer *et al*. 1984, Vidal and Smith 1986, Springer *et al*. 1987, Springer 1998). In at least one case, the slope of the relationship between temperature and a biological variable (positive or negative) depends on the nature of the meteorological regime (positive or negative anomaly of the Pacific Decadal Oscillation), adding a further complication to our attempts to understand functional relationships in the ecosystem.

And there are other time scales of change that further confuse our understanding of how the ecosystem behaves. The PDO and El Nino events are superimposed on longer-term trends and oscillations in climate of 50 to 100 years duration and longer (Keigwin 1996, Minobe 1997, Springer 1998). Because many contemporary changes in biology demonstrate compelling relationships to physical conditions, and because some very-long-term data sets show how populations have fluctuated since long before the influence of people became an issue in marine ecosystems (Baumgartner *et al*. 1992), we should not necessarily be alarmed over recent events. Change is normal and it must be accommodated: ecosystems have mechanisms to deal with it and so must people. However, there may be times when remedial, perhaps drastic, actions must be taken to conserve species of economic, aesthetic, and ecosystem importance, especially when the actions of people are at the heart of the problem.

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MARINE MAMMAL-SEA ICE RELATIONSHIPS

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Species of Major Concern Relative to Climate Change in the Alaskan Arctic

The marine mammal fauna off western and northern Alaska is particularly diverse, largely because of the great number of temperate/subarctic species that occur in the Bering Sea (Table 1). Although changes in the environment resulting from climate change may affect the distribution and abundance of those species also, this review will focus on the Arctic/subarctic marine mammals that are of particular importance to coastal residents of Alaska. Those species include: spotted, bearded, and ringed seals, walrus, polar bears, and bowhead and beluga whales. A brief description of the distribution and abundance of each species is given below. Additional details can be found in Lowry *et al*. (1982), Lentfer (1988), National Research Council (1996), and Hill and DeMaster (1998).

Spotted seals are widely distributed in the North Pacific, generally occurring in areas that are seasonally covered with sea ice. They range westward from Bristol Bay to Kamchatka, then south into the Sea of Japan. During summer they move northward into the Chukchi, Beaufort, and East Siberian seas. From November through May or June they are found in the sea ice. In spring they are seen hauled out singly or in small groups, mostly in the ice front where the floes are not too congested and move freely. In summer and early fall they occur mostly in open water areas and may be seen hauled out in groups of 1,000 or more on sandy spits and bars along the coast. Spotted seals are common off Alaska and their population may number 100,000 or more. However, there hasn't been a satisfactory method developed for estimating total population size.

Bearded seals are found in ice-covered regions of the Arctic, mostly over relatively shallow continental shelves. In the winter bearded seals occur in the ice front habitat used by spotted and ribbon seals, and also farther north in the pack ice wherever the ice is in motion and there is some open water. They are ice-associated throughout the year, and therefore move north and south as the ice retreats in the summer and advances in the winter. According to coastal residents, some weaned pups do not move northward but spend their first summer and fall feeding in freshwater estuaries along the Bering and Chukchi coasts. The population size of bearded seals has never been accurately estimated for the Bering/Chukchi seas, or anywhere else for that matter. They are obviously a common animal, and there is no indication that their numbers have changed in recent years.

Ringed seals occur throughout the Arctic basin. During winter the highest densities of adult seals occur on the shorefast ice which is the most stable platform for pupping. In summer they occur in the drifting ice and open water areas. Off western Alaska where the seasonal ice disappears from the Bering Sea and most of the Chukchi Sea during summer, ringed seals probably move northward to follow the ice. In regions like the Beaufort Sea where the ice moves a relatively short distance offshore during summer the seals are probably much less migratory. Ringed seals are quite abundant. Given the huge area they occupy, their worldwide population is almost certainly in the millions. Seal densities vary by location, ice type, and year. Over the long-term it is likely that the ringed seal population off Alaska is fairly stable and healthy.

Walrus are circumpolar and occur in the Arctic and its peripheral seas. The entire Alaskan walrus population spends winter and spring in the sea ice, mostly in the Bering Sea. The female-calf part of the population, which moves northward with the retreating ice in spring, usually spends the summer along the edge of the ice pack in the Chukchi Sea. Most adult males stay south of the ice in the summer, using terrestrial haulouts in Chukotka and Alaska. Aerial surveys conducted in 1975-1990 by researchers from the U.S. and Russia suggested that the population numbered something in excess of 200,000. There have been no population surveys done since 1990. Research to look at the age/sex composition of walrus herds summering in the Chukchi Sea suggests that calf production and survival have been low in recent years.

Polar bears are widely distributed in the Arctic. There are two populations off Alaska: the northern population that stays mostly in the Beaufort Sea, and the western population that occurs in the Chukchi and Bering seas. Some pregnant adult females spend the winter months in dens on land, but otherwise they live most of their life on the sea ice. Polar bear populations are difficult to census. The northern population is estimated at about 1,800 animals. The western population may number 2,000-5,000.

Bowhead whales range seasonally through the Bering, Chukchi, and Beaufort Seas. They are thought to winter mostly in drifting ice in the central Bering Sea, then move northward in spring through leads in the ice that take them to Banks Island in Canada. From there they move southward and spend summer feeding in the eastern Beaufort Sea and Amundsen Gulf before migrating westward then southward back into the Bering Sea. The most recent abundance estimate for Bering-Chukchi-Beaufort bowheads is 8,200, with the population size increasing at about 3% per year.

Beluga whales that occur off western Alaska comprise four separate stocks. It is thought that they all winter in drifting ice in the Bering Sea. In spring the Beaufort Sea stock migrates north and east along with the bowheads, and spends summer months in the Mackenzie Delta and adjacent parts of the eastern Beaufort Sea. In the fall they migrate westward across the Beaufort Sea, taking a northerly route through the ice. Whales from the eastern Chukchi Sea stock appear in the Kotzebue Sound-Kasegaluk Lagoon region in July, then migrate northward into the Beaufort Sea and Arctic Ocean. They presumably move southward into the Bering Sea in fall. The eastern Bering Sea and Bristol Bay stocks spend summer months along the coast of Alaska and do not seem to migrate nearly as far as the other two stocks. Currently it is thought that all western Alaska beluga whales stocks are healthy. Recent abundance estimates are: Beaufort Sea stock—39,258;

eastern Chukchi Sea stock—3,710; eastern Bering Sea stock—7,986; and Bristol Bay stock—1,555.

Ways that Climate Change Could Affect Marine Mammals

Changes in Physical Habitats

Fay (1974) provides an excellent description of the role of sea ice in the ecology of Bering Sea marine mammals. He lists the following functions that ice serves for pinnipeds: isolation, space, variety, food supply, transportation, sanitation, and shelter. For most cetaceans, ice has mainly a negative effect because it excludes them from areas they could otherwise use. However, for species adapted to the ice such as belugas and bowheads ice may provide a refuge from killer whale predation.

Global climate change could change sea ice characteristics in many ways. The nature of the ice itself could change--it could become thinner, floes could become smaller, and it could have more or less snow coverage. The distribution and characteristics of open water areas within the ice (leads and polynyas) could change. The overall distribution of sea ice could change, with shorefast ice becoming less extensive, and less area covered with drifting ice. The persistence of ice could change with ice forming later in the year and breaking up earlier and faster.

The various species of seals have adapted themselves to using ice with certain characteristics (Burns 1970, Fay 1974, Burns *et al*. 1981). These adaptations are particularly obvious during the pupping season. Ringed seals prefer to use stable landfast ice for pupping. To produce subnivean (under-snow) lairs for their pups they need adequate depths of snow on top of the ice. Bearded seal pups are born on moving ice, mostly in areas of fairly high ice concentrations. Spotted and ribbon seals pups are born mostly in the relatively dynamic ice front. Changes in ice thickness, snow depths, and timing of break-up would all be expected to influence pupping success for ice associated seals. For example, if there is less shorefast ice, more ringed seal pups will be born on moving ice where they are less likely to survive. Also, if shorefast ice breaks up earlier, ringed seal lairs will collapse more quickly and pups will be more exposed to predation (Burns 1970).

Seals haul out and bask for much of the time during their annual molt. Ice-associated pinnipeds molt on the ice during May-June. Earlier breakup of ice could result in a shorter time for molting, or it might cause seals to use land haulouts in order to complete the molt.

Ice associated pinnipeds use ice as a place to rest between feeding periods, and therefore it is important that the ice be near their food supply. Walruses are benthic feeders and they need to have ice near the shallow continental shelf where they can reach their food supply. In years such as 1990 when the summer ice edge was far north of the Chukchi Sea continental shelf, walrus needed to either haul out on land or make long swims to the south to reach their food supply (Gilbert *et al*. 1992).

Shorefast ice completely excludes cetaceans from nearshore areas. A reduction in the amount of shorefast ice could make some nearshore habitats available to them during winter-spring. Less drifting ice and a shorter ice season could have negative impacts on ice-associated cetaceans (bowheads and belugas) but could be an advantage for species that are not adapted to ice such as gray whales and killer whales (Moore and DeMaster 1998). Polynyas and leads are very important for the distribution and migration of bowheads in winter and spring (Moore and Reeves 1993), and changes in those features could have a major impact on bowhead behavior.

Climate change will likely result in changes in temperature regimes as a result of changes in ocean currents, sea ice coverage, and river flows (Tynan and DeMaster 1997). This could have both subtle and major effects on marine mammal distributions, in ways that are difficult to predict. One concern is with beluga whales that concentrate in traditional areas during summer months (Frost and Lowry 1990). Concentration areas are probably selected for a variety of reasons, one of which may be warm water that helps promote molting (St. Aubin *et al*. 1990). Changes in water temperatures in the coastal zone could therefore cause changes in beluga use of nearshore areas.

Changes in Food Availability

Global climate change is expected to have major effects on marine productivity and on the marine mammal prey species. Changes in temperature and currents will have variable impacts in different areas, and may depress or favor either pelagic or benthic food webs. The probable effects on marine mammal populations cannot be reliably predicted, but the following are some likely possibilities. Ringed seals depend quite a lot on an under-ice food web (Bradstreet and Cross 1982), and decreases in ice coverage and persistence could reduce the food available to them. Contrary to that prediction, Harwood and Stirling (1992) described reduced productivity of ringed seals in the eastern Beaufort Sea during the mid 1970s and mid 1980s that may have been due to reduced primary productivity caused by heavier than normal ice cover. Species with relatively narrow diets like gray whales (mostly benthic amphipods), walruses (mostly clams), and bowhead whales (mostly copepods) could be significantly impacted by changes in currents, sedimentation patterns, or primary productivity. Species with relatively broad diets, such as spotted seals and bearded seals, might be less affected.

Polar bears depend mostly on ringed seals for their food, and any changes in ringed seal abundance would likely result directly in changes to polar bear populations. Stirling *et al*. (1999) have conducted a long-term study of polar bears in western Hudson Bay, where bears hunt ringed seals on the sea ice from November-July then spend the open water season on shore where they basically fast. They found decreasing body condition and reproductive performance in bears that correlates with a trend toward earlier breakup in recent years. With an earlier breakup, bears have a shorter feeding season, they are less fat when the come ashore, and they must fast for a longer period.

Changes in Interspecific Interactions

As the distributions of various species adjust to climate change, interactions among species will also change. Diets will vary depending on the seasonal overlaps among marine mammals and their fish and invertebrate prey. Novel prey species may expose predators to new types of parasites, different environmental contaminants, etc. Distributional and climate changes may put marine mammals into contact with new disease agents (bacteria and viruses).

While marine mammal species show a great deal of ecological specialization, they undoubtedly compete with one another to some extent. An interesting example may be harbor seals and spotted seals, closely related species that show considerable ecological similarity. In western Alaska, spotted seals occur in areas that are seasonally ice-covered and harbor seals are more southern, but their distributions overlap somewhat in Bristol and Kuskokwim bays (Frost *et al*. 1983). One might predict that with increased water temperatures and decreases in sea ice coverage the boundary between the spotted seal and harbor seal populations would shift northward.

Predatory interactions are also likely to change with shifts in species distributions. Changes in seal distribution within the sea ice could bring them into more or less contact with polar bears. If ice-inhabiting seals or walrus are forced to haul out on land to complete their molt or to stay near food resources they could be more exposed to predators such as grizzly bears and wolves. If the overall amount of sea ice is less, ice inhabiting pinnipeds will be concentrated in a smaller area during the pupping season. Lowry and Fay (1984) documented an unusually high rate of predation by walrus on seal pups in 1979, a year of very light spring ice cover in the Bering Sea.

Relatively little is known about killer whales in western Alaska, but they are known to prey on whales, seals, and walruses (Lowry *et al*. 1987). Such predatory relationships could change as a result of climate changes, in ways that are impossible to predict. Changes in distribution and behavior of sharks could also result in different rates of predation on seals.

Conclusions

Currently in the scientific literature there is almost no documentation of effects of climate change on Arctic marine mammals. The only exception is with polar bears, where a direct link has been shown with changes in sea ice that limit the ability of bears to feed on ringed seals.

The overall effect of climate change on Arctic marine mammals will probably depend on the combined effects of changes in physical habitats, changes in prey populations, and changes in inter-species interactions. In general one might predict that distributions of most species would shift northward, and that populations of ice-associated species are likely to decline. Such changes would very likely have major effects on the availability of marine mammals to coastal Alaska Natives.

Currently there is reasonably good information available on the basic biology of most marine mammal species of concern. However, in almost all cases there is no detailed information on population size, population trend, habitat use, vital parameters, etc. Without additional research and monitoring it will be very difficult to detect changes in these populations, and virtually impossible to measure the changes or explain their causes.

Table 1. List of the marine mammal species in the Bering, Chukchi, and Beaufort seas (from National Research Council (1996)).

COMMON NAME	SCIENTIFIC NAME	ABUNDANCE/TREND*	STATUS**
Baleen Whales			
gray whale	*Eschrichtius robustus*	moderate/increasing	recovered
fin whale	*Balaenoptera physalus*	low/unknown	endangered
minke whale	*Balaenoptera acutorostrata*	low/unknown	unknown
blue whale	*Balaenoptera musculus*	low/unknown	endangered
sei whale	*Balaenoptera borealis*	low/unknown	endangered
humpback whale	*Megaptera novaeangliae*	low/unknown	endangered
right whale	*Balaena glacialis*	low/unknown	endangered
bowhead whale	*Balaena mysticetus*	low/increasing	endangered
Tooth Whales and Dolphins			
sperm whale	*Physeter macrocephalus*	moderate/unknown	endangered
Cuvier's beaked whale	*Ziphius cavirostris*	low/unknown	unknown
Baird's beaked whale	*Berardius bairdi*	low/unknown	unknown
Stejneger's beaked whale	*Mesoplodon stejnegeri*	low/unknown	unknown
beluga whale	*Delphinapterus leucas*	moderate/stable	OSP
killer whale	*Orcinus orca*	low/unknown	unknown
Dall's porpoise	*Phocoenoides dalli*	moderate/unknown	unknown
harbor porpoise	*Phocoena phocoena*	low/unknown	unknown
Pinnipeds			
northern fur seal	*Callorhinus ursinus*	high/stable	depleted
Steller sea lion	*Eumetopias jubatus*	moderate/declining	endangered
Pacific walrus	*Odobenus rosmarus divergens*	high/stable	OSP
harbor seal	*Phoca vitulina richardsi*	moderate/declining	unknown
spotted seal	*P. largha*	high/unknown	unknown
ribbon seal	*P. fasciata*	moderate/unknown	unknown
ringed seal	*P. hispida*	high/unknown	unknown
bearded seal	*Erignathus barbatus*	high/unknown	unknown
Others			
polar bear	*Ursus maritimus*	low/stable	OSP
sea otter	*Enhydra lutris*	moderate/stable	OSP

* low = fewer than 10,000; moderate = 10,000-100,000; high = more than 100,000.

** Endangered and threatened refer to Endangered Species Act listings. OSP means within the Optimum Sustainable Population range as defined by the Marine Mammal Protection Act. Depleted means below the OSP range.

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