Jacqueline M. Grebmeier
Wieslaw Maslowski *Editors*

The Pacific Arctic Region

Ecosystem Status and Trends in a Rapidly Changing Environment

Springer

The Pacific Arctic Region

Bering Strait region off Cape Prince of Wales, Alaska, USA (Photo credit : Elizabeth Labunski, US Fish & Wildlife Service)

Jacqueline M. Grebmeier • Wieslaw Maslowski
Editors

The Pacific Arctic Region

Ecosystem Status and Trends in a Rapidly Changing Environment

Springer

Editors
Jacqueline M. Grebmeier
Chesapeake Biological Laboratory
University of Maryland Center
for Environmental Science
Solomons, MD, USA

Wieslaw Maslowski
Department of Oceanography
Graduate School of Engineering and
Applied Sciences
Naval Postgraduate School
Monterey, CA, USA

ISBN 978-94-017-8862-5 ISBN 978-94-017-8863-2 (eBook)
DOI 10.1007/978-94-017-8863-2
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2014941794

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Dedication to Martin (Marty) Bergmann, February 19, 1956–August 20, 2011

Martin (Marty) Bergmann was Director of Canada's Polar Continental Shelf Program (PCSP) of Natural Resources Canada when he died at the age of 55 in the First Air B-737 plane crash on August 20, 2011, at Resolute Bay, Nunavut, Canada. He was traveling to Resolute to escort Prime Minister Stephen Harper on a tour of Canada's Arctic facilities.

Marty was a strong advocate for collaborative Arctic science and he was instrumental in developing the Pacific Arctic Group (PAG) in 2002, and he served as the forum's first Chair. PAG is an active nexus for international networking for marine programs in the Pacific Arctic region and the sponsor of this Springer volume. Marty worked diligently to provide opportunities for scientific interactions from all interested countries, including scientists, agency managers, politicians, and local community members. He facilitated many Arctic scientific programs leading up to the

2007–2008 International Polar Year (IPY), some that continue today and many of the results from which are presented in this volume. Marty will be remembered for his unbounded energy and efforts to move our understanding of the Arctic System forward.

Prior to taking on a leadership role at PCSP, Marty served as Director of the National Center for Arctic Aquatic Research Excellence in Fisheries and Oceans Canada, managing the logistics for Arctic Ocean science aboard the Canadian Coast Guard fleet. Marty had a suite of accomplishments, both in Canada through the highly successful IPY years and internationally by coordinating agreements to facilitate Arctic logistics and science activities with many countries, including Great Britain, the United States, China, Japan and the Republic of Korea.

In 2012 the Royal Canadian Geographical Society established the Martin Bergmann Medal for Excellence in Arctic Leadership and Science to recognize Marty's leadership for advancing science in the Arctic. Specifically, the award recognizes "achievement for 'excellence in Arctic leadership and science'. It celebrates "Marty" Bergmann, a public servant with an outstanding talent for networking that led him to connect scientists with resources and technology, to inspire business leaders, explorers and innovators towards new goals and to consider and attempt to meet the challenges inherent in opening up the Arctic, whether these were related to logistics, safety, resources, people, knowledge or will."

Marty was posthumously awarded the inaugural medal at the 2012 International Polar Year Conference in Montreal, Canada.

With these memories of his efforts on behalf of Arctic science in our hearts and minds, we dedicate this volume to our friend, Marty Bergmann, as we work to better our understanding of the Arctic system for future generations.

Jackie Grebmeier
Chair of the Pacific Arctic Group (PAG)
and Wieslaw Maslowski, co-editor

Contents

1 **The Pacific Arctic Region: An Introduction** 1
Jacqueline M. Grebmeier and Wieslaw Maslowski

2 **Recent and Future Changes in the Meteorology of the Pacific Arctic** 17
James E. Overland, Jia Wang, Robert S. Pickart, and Muyin Wang

3 **Recent Variability in Sea Ice Cover, Age, and Thickness in the Pacific Arctic Region** 31
Karen E. Frey, James A. Maslanik, Jaclyn Clement Kinney, and Wieslaw Maslowski

4 **Abrupt Climate Changes and Emerging Ice-Ocean Processes in the Pacific Arctic Region and the Bering Sea** 65
Jia Wang, Hajo Eicken, Yanling Yu, Xuezhi Bai, Jinlun Zhang, Haoguo Hu, Dao-Ru Wang, Moto Ikeda, Kohei Mizobata, and James E. Overland

5 **The Large Scale Ocean Circulation and Physical Processes Controlling Pacific-Arctic Interactions** 101
Wieslaw Maslowski, Jaclyn Clement Kinney, Stephen R. Okkonen, Robert Osinski, Andrew F. Roberts, and William J. Williams

6 **Shelf-Break Exchange in the Bering, Chukchi and Beaufort Seas** 133
William J. Williams, Emily Shroyer, Jaclyn Clement Kinney, Motoyo Itoh, and Wieslaw Maslowski

7 **On the Flow Through Bering Strait: A Synthesis of Model Results and Observations** 167
Jaclyn Clement Kinney, Wieslaw Maslowski, Yevgeny Aksenov, Beverly de Cuevas, Jaromir Jakacki, An Nguyen, Robert Osinski, Michael Steele, Rebecca A. Woodgate, and Jinlun Zhang

8 Carbon Fluxes Across Boundaries in the Pacific Arctic Region in a Changing Environment 199
Wei-Jun Cai, Nicholas R. Bates, Laodong Guo, Leif G. Anderson, Jeremy T. Mathis, Rik Wanninkhof, Dennis A. Hansell, Liqi Chen, and Igor P. Semiletov

9 Carbon Biogeochemistry of the Western Arctic: Primary Production, Carbon Export and the Controls on Ocean Acidification 223
Jeremy T. Mathis, Jacqueline M. Grebmeier, Dennis A. Hansell, Russell R. Hopcroft, David L. Kirchman, Sang H. Lee, S. Bradley Moran, Nicholas R. Bates, Sam VanLaningham, Jessica N. Cross, and Wei-Jun Cai

10 Biodiversity and Biogeography of the Lower Trophic Taxa of the Pacific Arctic Region: Sensitivities to Climate Change 269
R. John Nelson, Carin J. Ashjian, Bodil A. Bluhm, Kathleen E. Conlan, Rolf R. Gradinger, Jacqueline M. Grebmeier, Victoria J. Hill, Russell R. Hopcroft, Brian P.V. Hunt, Hyoung M. Joo, David L. Kirchman, Ksenia N. Kosobokova, Sang H. Lee, William K.W. Li, Connie Lovejoy, Michel Poulin, Evelyn Sherr, and Kelly V. Young

11 Marine Fishes, Birds and Mammals as Sentinels of Ecosystem Variability and Reorganization in the Pacific Arctic Region 337
Sue E. Moore, Elizabeth Logerwell, Lisa Eisner, Edward V. Farley Jr., Lois A. Harwood, Kathy Kuletz, James Lovvorn, James R. Murphy, and Lori T. Quakenbush

12 Progress and Challenges in Biogeochemical Modeling of the Pacific Arctic Region 393
Clara J. Deal, Nadja Steiner, Jim Christian, Jaclyn Clement Kinney, Ken L. Denman, Scott M. Elliott, Georgina Gibson, Meibing Jin, Diane Lavoie, Sang H. Lee, Warren Lee, Wieslaw Maslowski, Jia Wang, and Eiji Watanabe

Index 447

Contributors

Yevgeny Aksenov Marine Systems Modelling, National Oceanography Centre, Southampton, UK

Leif G. Anderson Department of Chemistry, University of Gothenburg, Gothenburg, Sweden

Carin J. Ashjian Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Xuezhi Bai Cooperative Institute for Limnology and Ecosystems Research (CILER), School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI, USA

Nicholas R. Bates Bermuda Institute of Ocean Sciences (BIOS), Ferry Reach, Bermuda

Bodil A. Bluhm School of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Fairbanks, AK, USA

Wei-Jun Cai School of Marine Science and Policy, The University of Delaware, Newark, DE, USA

Liqi Chen Third Institute of Oceanography, The State Oceanic Administration of China, Xiamen, China

Jim Christian Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, BC, Canada and the Canadian Centre for Climate Modeling and Analysis, Environment Canada, Victoria, BC, Canada

Kathleen E. Conlan Canadian Museum of Nature, Ottawa, ON, Canada

Jessica N. Cross School of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Fairbanks, AK, USA

Beverly de Cuevas Marine Systems Modelling, National Oceanography Centre, Southampton, UK

Clara J. Deal International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA

Ken L. Denman School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada

Hajo Eicken Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA

Lisa Eisner Alaska Fisheries Science Center, National Oceanic and Atmospheric Administration, Seattle, WA, USA

Scott M. Elliott Climate Ocean Sea Ice Modeling, Los Alamos National Laboratory, Los Alamos, NM, USA

Edward V. Farley Jr. Alaska Fisheries Science Center, National Oceanic and Atmospheric Administration, Seattle, WA, USA

Karen E. Frey Graduate School of Geography, Clark University, Worcester, MA, USA

Georgina Gibson International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA

Rolf R. Gradinger School of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Fairbanks, AK, USA

Jacqueline M. Grebmeier Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD, USA

Laodong Guo School of Freshwater Sciences, University of Wisconsin-Milwaukee, Milwaukee, WI, USA

Dennis A. Hansell Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA

Lois A. Harwood Canada Department of Fisheries and Oceans, Yellowknife, NT, Canada

Victoria J. Hill Department of Ocean, Earth and Atmospheric Sciences, Old Dominion University, Norfolk, VA, USA

Russell R. Hopcroft School of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Fairbanks, AK, USA

Haoguo Hu Cooperative Institute for Limnology and Ecosystems Research (CILER), School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI, USA

Brian P.V. Hunt Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada

Moto Ikeda Graduate School of Earth and Environmental Sciences, Hokkaido University, Sapporo, Japan

Motoyo Itoh Japan Agency for Marine-Earth Science and Technology, Yokosuka-city, Kanagawa, Japan

Jaromir Jakacki Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland

Meibing Jin International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA

Hyoung M. Joo Korea Polar Research Institute, Incheon, South Korea

Jaclyn Clement Kinney Department of Oceanography, Graduate School of Engineering and Applied Sciences, Naval Postgraduate School, Monterey, CA, USA

David L. Kirchman School of Marine Science and Policy, University of Delaware, Lewes, DE, USA

Ksenia N. Kosobokova Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russian Federation

Kathy Kuletz USF&WS, Alaska Region, Anchorage, AK, USA

Diane Lavoie Maurice Lamontagne Institute, Fisheries and Oceans Canada, Mont Joli, QC, Canada

Sang H. Lee Department of Oceanography, Pusan National University, Busan, South Korea

Warren Lee Canadian Centre for Climate Modeling and Analysis, Environment Canada, Victoria, BC, Canada

William K.W. Li Fisheries and Oceans Canada, Dartmouth, NS, Canada

Elizabeth Logerwell Alaska Fisheries Science Center, National Oceanic and Atmospheric Administration, Seattle, WA, USA

Connie Lovejoy Department of Biology, Université Laval, Quebec, QC, Canada

James Lovvorn Southern Illinois University, Carbondale, IL, USA

James A. Maslanik Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO, USA

Wieslaw Maslowski Department of Oceanography, Graduate School of Engineering and Applied Sciences, Naval Postgraduate School, Monterey, CA, USA

Jeremy T. Mathis Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, WA, USA and School of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Fairbanks, AK, USA

Kohei Mizobata Department of Ocean Sciences, Tokyo University of Marine Science and Technology, Tokyo, Japan

Sue E. Moore Fisheries Office of Science and Technology, National Oceanic and Atmospheric Administration, Seattle, WA, USA

S. Bradley Moran Graduate School of Oceanography, University of Rhode Island, Narragansett, RI, USA

James R. Murphy Alaska Fisheries Science Center, National Oceanic and Atmospheric Administration, Seattle, WA, USA

R. John Nelson Department of Biology, Centre for Biomedical Research, University of Victoria, Victoria, BC, Canada

An Nguyen Program in Atmospheres, Oceans, and Climate, Massachusetts Institute of Technology, Cambridge, MA, USA

Stephen R. Okkonen School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, AK, USA

Robert Osinski Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland

James E. Overland Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, WA, USA

Robert S. Pickart Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Michel Poulin Canadian Museum of Nature, Ottawa, ON, Canada

Lori T. Quakenbush Alaska Department of Fish and Game, Fairbanks, AK, USA

Andrew F. Roberts Department of Oceanography, Naval Postgraduate School, Monterey, CA, USA

Igor P. Semiletov Pacific Oceanological Institute, Far Eastern Branch of the Russian, Academy of Sciences, Vladivostok, Russia and International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA

Evelyn Sherr College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA

Emily Shroyer College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA

Michael Steele Applied Physics Laboratory, University of Washington, Seattle, WA, USA

Nadja Steiner Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, BC, Canada and the Canadian Centre for Climate Modeling and Analysis, Environment Canada, Victoria, BC, Canada

Sam VanLaningham School of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Fairbanks, AK, USA

Dao-Ru Wang Hainan Marine Development and Design Institute, Hainan, China

Jia Wang Great Lakes Environmental Research Laboratory (GLERL), National Oceanic and Atmospheric Administration, Ann Arbor, MI, USA

Muyin Wang Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, WA, USA

Rik Wanninkhof Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL, USA

Eiji Watanabe International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA and Research and Development Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

William J. Williams Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, BC, Canada

Rebecca A. Woodgate Applied Physics Laboratory, University of Washington, Seattle, WA, USA

Kelly V. Young Fisheries and Oceans Canada, Sidney, BC, Canada

Yanling Yu Arctic Science Center, Applied Physics Laboratory, University of Washington, Seattle, WA, USA

Jinlun Zhang Applied Physics Laboratory, University of Washington, Seattle, WA, USA

Chapter 1
The Pacific Arctic Region: An Introduction

Jacqueline M. Grebmeier and Wieslaw Maslowski

Abstract The Pacific Arctic region (PAR) is experiencing atmospheric changes, rapid seasonal sea ice retreat, seawater warming, regional ocean acidification, along with other environmental changes and biological responses in lower to upper trophic organisms. Both physical and biogeochemical modeling indicate the potential for step-function changes to the overall ecosystem, both under current and in the projected conditions. This volume of synthesis papers was coordinated within the Pacific Arctic Group (PAG), a network of international partners undertaking and facilitating collaborative research in the Pacific influenced Arctic seas and basin. It also serves as a product of activities from the 2007–2008 International Polar Year. The topics range from atmospheric and physical sciences to chemical processing and biological response to changing environmental conditions. Physical and biogeochemical modeling results highlight the need for continued data collection together with interdisciplinary modeling activities to track and forecast the changing ecosystem of the Pacific Arctic in response to climate change.

Keywords Pacific Arctic Region • Physical forcing • Ecosystem response • Climate change

J.M. Grebmeier (✉)
Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, 146 Williams Street, Solomons, MD 20688, USA
e-mail: jgrebmei@umces.edu

W. Maslowski
Department of Oceanography, Graduate School of Engineering and Applied Sciences, Naval Postgraduate School, Dyer Road, Bldg. SP339B, Monterey, CA 93943, USA
e-mail: maslowsk@nps.edu

J.M. Grebmeier and W. Maslowski (eds.), *The Pacific Arctic Region: Ecosystem Status and Trends in a Rapidly Changing Environment*, DOI 10.1007/978-94-017-8863-2_1,

1.1 Introduction

The Pacific Arctic Region (PAR) synthesis effort presented in this volume is an ongoing contribution of the Pacific Arctic Group (PAG) to better understand the processes inherent in controlling and sustaining the marine ecosystem and projected drivers of change in the region. PAG is an international consortium of scientists, agency managers and organizations interested in scientific progress and collaboration in the Pacific Arctic. The PAG definition of the Pacific Arctic extends from the northern Bering Sea into the Chukchi Sea and adjacent Arctic seas, and extending into the deep basins of the Arctic Ocean.

The core objectives of the PAR synthesis activities within PAG are to: (1) present new synthetic results from observational and modeling activities in the Pacific-influenced Arctic region, (2) characterize current status and trends of the ecosystem to improve our understanding of the state and key processes influencing the marine system, (3) use model projections to evaluate ongoing processes and future evolution of the physical, biogeochemical and biological system to guide new science activities, and (4) to identify critical marine components for further development of observational networks in the Pacific Arctic.

As a core contribution to the PAG synthesis efforts, PAG members initiated the current synthesis book. The chapters in this book are multi-disciplinary with a systems approach, including retrospective, field, and modeling efforts. The chapter format is thematic in content, with spatial regions inside the chapters used as case studies to evaluate the Pacific Arctic region. The overarching themes are process-oriented, and consider both temporal and spatial scales. The modeling chapters cover a larger spatial domain, including the Pacific inflow through the Aleutian Islands/southern Bering Sea (upstream), while maintaining the main focus on the northern Bering, Chukchi, and Beaufort Seas, western Arctic Ocean basin as well as the downstream connectivity of the Pacific to Atlantic side, including the Canadian Arctic Archipelago.

Multiple PAG workshops and contributions set the stage for the various synthesis chapters in this book. For example, the first PAG workshop was held in Sanya, China, in January 2008, which resulted in a special issue in the Chinese Journal of Polar Science (Wang et al. 2008). The second PAG workshop, focused on biological processes, was held in May 2009 in Seattle, Washington, USA, resulting in a feature article for EOS (Grebmeier et al. 2010) and a workshop report. The third PAG workshop was focused on the marine carbon cycle, and was held in June 2009 in Xiamen, China and resulted in a special issue of Deep-Sea Research II (DSR II; Cai et al. 2012). Another special issue of scientific findings is being assembled in a DSR II special issue related to the Korean Arctic Expeditions during 2008–2010 (Sang Lee et al. 2013, personal communication). We introduce here this current book volume of synthesis chapters. The book concept was endorsed by the International Arctic Science Committee (IASC), the past Arctic Ocean Sciences Board (AOSB, now the Marine Working Group of IASC), and the IPY project office of the International Council of Science Unions (ICSU) also endorsed the volume as an IPY legacy effort.

During the course of this synthesis effort other interdisciplinary programs have been carried out in various sections of the PAR, many providing data supporting the syntheses in this volume. These programs include, but are not limited to the Bering Sea Project (Weise et al. 2012), the Bowhead Whale Feeding Ecology Study (BOWFEST) project (Ashjian et al. 2010), Canada's Three Ocean (C30) project (Carmack et al. 2010), the Chukchi Acoustic, Oceanographic, and Zooplankton (CHAOZ) study (Berchok et al. 2014), the Chukchi Sea Monitoring in Drilling Area-Chemistry and Benthos (COMIDA-CAB) project (Dunton et al. 2014), the Chukchi Sea Environmental Studies Program (CSESP; Day et al. 2013), the Distributed Biological Observatory (DBO) program (Grebmeier et al. 2010), the Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment (ICESCAPE) project (initial results reported in Arrigo et al. 2012), and the Russian-American Long-term Census of the Arctic (RUSALCA) program (Bluhm et al. 2010), along with other multidisciplinary studies by PAG member countries and other international collaborators.

1.2 The Pacific Arctic Region

Pacific water transiting across the wide Bering, Chukchi and the eastern portion of the East Siberian shelves, and western portion of the Beaufort Sea, is a major driving force for the physical environmental state, ice extent and thickness, productivity and carbon transport in the Amerasian Arctic (Fig. 1.1). There are key physical, biogeochemical, and biological oceanographic features that distinguish the PAR from the rest of the Arctic Ocean. Hydrographic characteristics and distribution of Pacific water have important implications for shelf productivity as well as shelf-basin exchange at the continental margins, including the downstream influence that Pacific water has on the upper halocline below and sea ice above in the Arctic Basin as well as in the Canadian Arctic Archipelago.

1.3 Physical Processes, Hydrography and Sea Ice: Field and Modeling

The Bering Strait region is a major gateway from the perspective of transport of sea ice and ocean volume and properties, including heat, freshwater and nutrients, and fluxes of atmospheric heat and moisture (Cooper et al. 1997; Overland and Stabeno 2004; Shimada et al. 2006; Woodgate and Aagaard 2005). It also plays a central role as a pathway for fluxes of biological organisms and organic carbon (Grebmeier et al. 2006a; Grebmeier 2012; Walsh et al. 2004). Seasonal evaluation of time series measurements (1990–2010) from the Bering Strait indicate annual variability in salinity, temperature, and transport (Woodgate et al. 2012). Recently it has been determined that the freshwater flux in Bering Strait has likely been

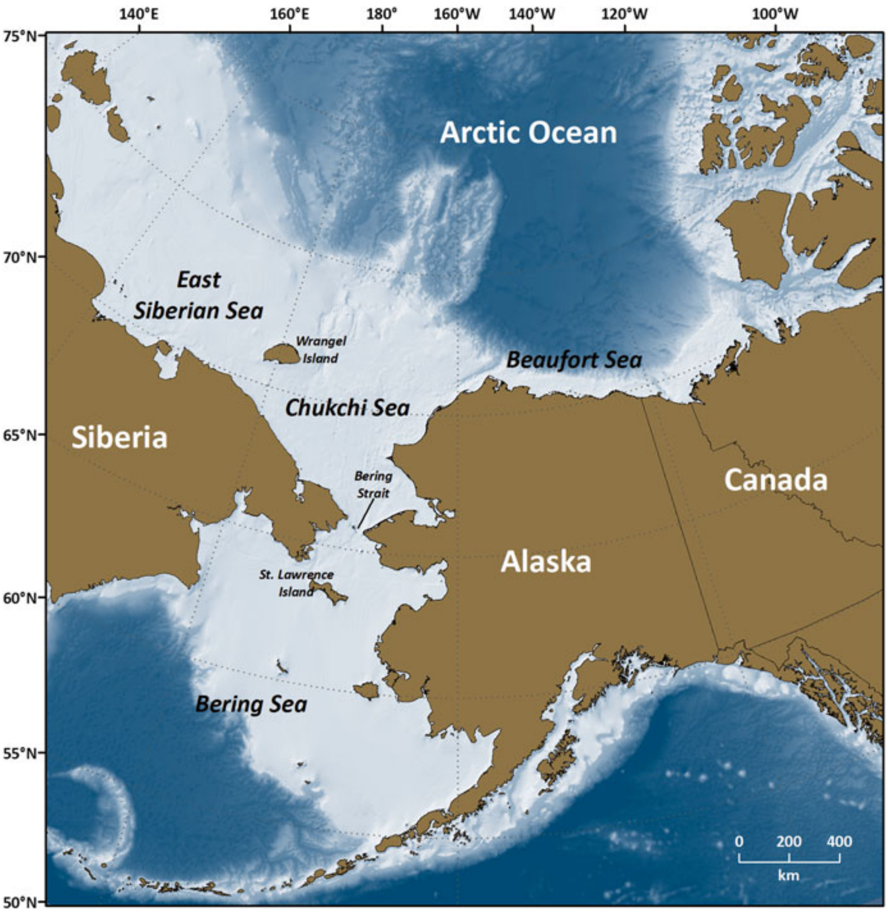

Fig. 1.1 Schematic of the Pacific Arctic Region, including the Bering, Chukchi, East Siberian and Beaufort Seas and the Arctic Ocean

underestimated and should be revised upwards (Woodgate and Aagaard 2005). While these estimates require further verification (since continuous moored measurements have been limited to deeper, more saline waters of Bering Strait) the newer flux estimates indicate that freshwater in Bering Strait may provide ~40 % of the total freshwater input to the Arctic Ocean (Woodgate and Aagaard 2005).

The nutrient-rich Pacific waters transiting through the Bering Strait are transformed seasonally by oceanographic processes over the wide continental shelves south and north of the strait, with far-reaching implications for Arctic halocline formation and basin dynamics. Changes in the freshwater flux may also potentially influence thermohaline circulation in the global ocean. Both winter and summer Pacific Water types play variable, yet distinct roles in the transport of heat, freshwater, nutrients, carbon, and biological organisms northwards through the Bering

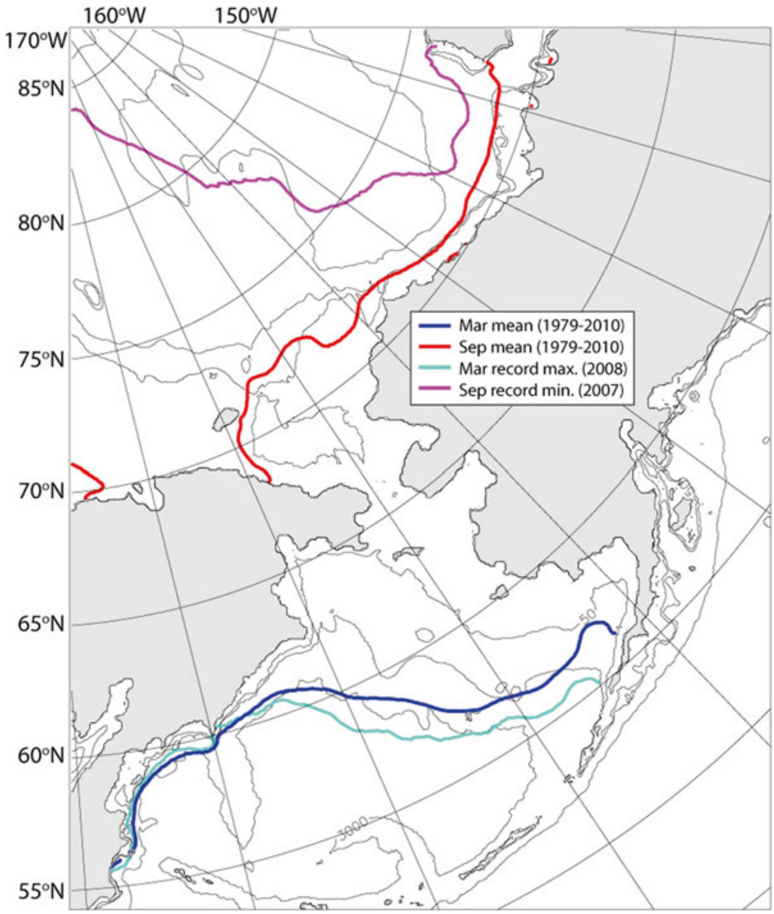

Fig. 1.2 Mean and extremes for March and September sea ice extent in the Pacific Arctic Region. *Colour contour lines* represent respective SSM/I sea ice extents (defined as 15 % concentration) from Comiso (2012)

Strait. Shimada et al. (2006) showed that summer Pacific water is a source of heat to the PAR and it is particularly significant over the Chukchi Borderland. Winter Pacific water is influenced by ice formation and brine rejection, so the timing, extent and location of these processes are intimately tied to halocline formation.

The PAR is experiencing the greatest seasonal retreat and thinning of sea ice in the Arctic (Fig. 1.2). September 2007, at the start of IPY, at that point, marked the highest seasonal sea ice retreat on record (Stroeve et al. 2007); this record was eclipsed in 2012 (Stroeve et al. 2012). Changes in sea ice formation, extent and thickness influence albedo feedback, brine formation and halocline maintenance, so atmosphere-ice-ocean interactions and dynamics are extremely critical for regulating climatic conditions in the Arctic, and can have global ramifications. Exchange of materials from shelf to slope and into the deep Arctic basin is also expected to be influenced by these changing conditions.

Key physiographic features of the shelf-slope region of the East Siberian, Chukchi and Beaufort Seas also influence shelf-basin exchange. In particular, Herald Valley/Canyon and Barrow Canyon are key conduits for transformed Pacific water and associated organisms that transit the Chukchi shelf to the deep Arctic Basin. Eddy formation and fluxes, boundary current dynamics, and advection are some of the critical transport mechanisms at the shelf-basin interface that facilitate the transfer of freshwater/salt, heat, nutrients, and various forms of organic and inorganic carbon that dictate the current state of the Arctic Ocean. Recent findings show increased northward heatflow within the Atlantic water transiting through Fram Strait into the deep Arctic Basin (Walczowski et al. 2012), which may increase advection of warmer Atlantic water and its impacts along the continental margins of the Chukchi and Beaufort seas (Pickart et al. 2011; Schulze and Pickart 2012).

Arctic systems can be rich and diverse habitats for marine life in spite of the extreme cold environment (Grebmeier et al. 2006a, 2010). Biogeochemical cycling processes and biological communities are directly influenced by changing sea ice extent, light availability, seawater hydrography (nutrients, salinity, temperature, density), currents, and water column production. Earlier seasonal sea ice melt and retreat in the Bering Sea and western Arctic will have dramatic impacts on the biological system, such as changes in overlying primary production, altering organic carbon transformation, pelagic-benthic coupling, and benthic production and community structure that could have cascading effects to higher trophic levels, which are of importance for local indigenous residents of the Arctic. Some specific examples of biological changes include time-series observations that indicate declines in bottom-dwelling clam populations and diving seaducks over the last few decades (Grebmeier et al. 2006b). In addition, a decline in benthic amphipod populations in the Chirikov Basin just south of Bering Strait has likely influenced the movement of migrating gray whales to feeding areas north of Bering Strait during this time period (Moore et al. 2003; Moore 2008).

Retreating sea ice and warming temperatures have increased coastline erosion of terrigenous materials into the coastal environment. An increased seasonal open water period in the Arctic results in increased wave fetch, leading to additional shoreline erosion. The subsequent input of old, terrestrially-produced carbon into the ocean could alter microbial transformation processes as well as dilute the labile marine carbon pool with less-usable terrigenous material, with a potential negative impact on food availability to marine organisms. The cycling of carbon (particulate, dissolved, inorganic) is a key concern in these extremely productive regions of the Arctic Ocean. Changes in these processes will have cascading impacts to all components of the ecosystem (from bacteria to man). Ocean acidification is a potential, large-scale negative impact on the Arctic marine carbon system since increased atmospheric CO_2 will reduce the buffering capability of seawater and increase corrosive trends (Mathis et al. 2007).

The following summaries highlight findings in each of the subsequent chapters of this book from atmospheric and physical forcing, biogeochemical cycling, biological processes and modeling efforts.

1.4 Atmospheric Forcing and Sea Ice

In Chap. 2, Overland et al. (2014, this volume) discuss the meteorological setting of the Pacific Arctic as the transition zone between the relatively warm and moist air mass of the North Pacific and cold and dryer air mass of the Arctic. The northern part of the PAR is dominated by high surface atmospheric pressure, but low-pressure cyclonic systems can propagate from the south, where the semi-permanent low pressure center, the Aleutian Low, is located. This latitudinal sea level pressure gradient results in predominantly easterly winds, which generate upwelling favorable conditions along the Beaufort and Chukchi continental slopes. Climate change in the Pacific Arctic is not occurring in a single phase, as the western Arctic Ocean proper has experienced warming and retreating sea ice cover in summer that has accelerated since the late 1990s, while the Bering Sea has had extended sea ice cover and much colder temperatures in winter and spring since 2006. Overland et al. also review coupled climate model predictions of climate change, which suggest increased interannual variability but relatively slow changes in seasonal sea ice cover trends and temperature in the Bering Sea during its sea ice covered season. This is in contrast to model predictions of a significant reduction of, or no, seasonal sea ice cover in the Chukchi Sea from July to November within the next couple decades. These changes will have major ecological impacts and could also lead to increased commercial activities that will take advantage of longer open-water seasons.

In Chap. 3, Frey et al. (2014, this volume) continue this theme of understanding the variability in sea ice conditions in the PAR, by synthesizing observational data and model results, and discuss the range of effects from the minimal change in the northern Bering Sea to the rapid and dramatic decline of sea ice cover in the Bering Strait region north of St. Lawrence Island, the Chukchi Sea and Canada Basin. Both earlier spring breakup and later sea ice formation occur in these seasonally changing sea ice regions, with portions of the Chukchi Sea experiencing the most extreme trends. Another common characteristic of the region is the widespread transition from multi-year ice to thinner, first year ice. Frey et al. discuss the implications of reduced sea ice areal coverage, age, and thickness on the overall productivity of the ecosystem that are discussed in more detail in later chapters of this book.

In Chap. 4, Wang et al. (2014, this volume) consider large-scale atmospheric patterns and how these patterns influence sea ice decline and other changes in the Pacific Arctic. In particular, they argue that in addition to the Arctic Oscillation (AO), the Dipole Anomaly (DA), which is a second mode of northern hemisphere sea level pressure variability, might be driving declines of sea ice cover. Wind anomalies associated with DA are typically meridional (north-south), hence their impact on sea ice distribution (e.g. its northward retreat or export through Fram Strait) may be more significant than the larger variability associated with zonal winds, which are driven by the AO. Meridional wind anomalies can also affect northward advection of warm Pacific water across the Chukchi shelf and reduction or persistence of landfast ice along the Beaufort and Chukchi coast. Wang et al. suggest a possible air-ice-sea feedback loop in the western Arctic involving DA, however the origins and controls of these modes require further investigations, including observations and modeling of the fully coupled Arctic System at process scales.

1.5 Physical Processes and Modeling

In Chap. 5, Maslowski et al. (2014, this volume) review the regional ocean circulation over an extended PAR, starting from the northern North Pacific into the western Arctic Ocean. They argue that upstream circulation of the Alaskan Stream and variability in fluxes across the Aleutian Island passes not only regulate the hydrology of the deep Bering Sea but also influence characteristics (especially salinity) of water advected onto the Bering Shelf and crossing Bering Strait. They envision the Bering Slope Current as more of a system of eddies generated along the slope rather than a continuous current. Year-round high eddy kinetic energy along the slope and in Anadyr and Bering straits is simulated just upstream of highly productive regions along the outer Bering shelf, in the Chirikov Basin that is north of St. Lawrence Island and again north of Bering Strait. This suggests strong regional biophysical coupling and indicates needs for development of improved modeling capabilities. Further downstream, in the Chukchi Sea, Maslowski et al. emphasize the importance of the Alaska Coastal Current in transporting heat via warm shelf waters into the Arctic Ocean basin. They find little or no correlation between modeled heat fluxes through Bering Strait and those entering the Beaufort Sea, which implies that most of the heat transiting across Bering Strait exchanges heat by melting ice or by transfer to the atmosphere within the Chukchi shelf. The water exported into the Beaufort Sea is instead warmed locally due to insolation, which increases with earlier retreat of sea ice cover. Winds and eddies distribute warm water further north and often under the ice cover. The authors hypothesize that some of the heat associated with this water (in particular that available below the shallow mixed layer) is not removed to the atmosphere during freeze up and instead it has been accumulating below the mixed layer in the western Arctic Ocean. This ‘new’ source of heat is available year around for entrainment into the mixed layer to reduce sea ice growth in winter and to accelerate its melt in summer.

In Chap. 6, Williams et al. (2014, this volume) focuses on shelf-break exchanges and associated processes within the Pacific Arctic. In particular, the authors consider ocean dynamics along the continental slope in the Bering, and in the Chukchi and Beaufort Seas, which define the southern and northern edges of the shelf system, respectively, that separate the North Pacific from the Arctic Ocean. Ocean on-shelf transport of volume and properties in the Bering Sea is concentrated in submarine canyons, especially in Zhemchug and Bering canyons, where mesoscale eddies within the Bering Slope Current are commonly observed (via remote sensing) and can also be modeled. Similarly on the northern end of the Bering-Chukchi shelf system, Herald and Barrow Canyons control the outflow into the deep basin. This outflow interacts with the shelf-break jets, resulting in instabilities and eddies, which in addition to wind-driven cross-slope fluxes in the Ekman (surface and bottom) boundary layers determine shelf-basin exchange along the Chukchi and Beaufort slopes. In addition, on-shelf upwelling of Atlantic water due to easterly winds in summer and the outflow of dense shelf water formed in polynyas due to brine rejection in winter can further affect shelf-basin exchange. Even though numerical models are the primary tool in quantifying such exchanges and their variability, models need to be evaluated and constrained by observations, which is why the authors argue for new field programs focused on shelf-break and processes there.

In Chap. 7, Clement-Kinney et al. (2014, this volume) focus on the flow through Bering Strait, the only connection between the Pacific and the Arctic. The physiographic narrow and shallow features of the strait has been challenging to apply to ocean general circulation models, using relatively coarse grids, and to realistically represent volume and property fluxes. A synthesis of observations and models presented in this chapter includes quantified fluxes of heat and freshwater and their seasonal and interannual variability. The models give reasonable estimates of volume transport compared to observational estimates, but uncertainty still remains in both. It is likely the existing models do not simulate well the narrow (10 km wide) flow of Alaska Coastal Current on the eastern margin of the strait where there is significant horizontal and vertical velocity shear and may be due to the lateral and vertical boundary conditions used. However, the available continuous observations are still limited as they do not measure the upper part of the water column with higher freshwater fractions and observational flux estimates assume homogeneity of the flow at all locations in the strait. Clement-Kinney et al. expect that further refinements of both model and observational estimates of volume flux at Bering Strait are needed, including higher spatial model resolution (both horizontal and vertical) and increased numbers of moorings. Since property fluxes are dependent on the volume transport, improved volume flux estimates are expected to reduce uncertainty of property fluxes.

1.6 Carbon Transformations and Cycling

In Chap. 8, Cai et al. (2014, this volume) evaluate the inflow of dissolved inorganic carbon (DIC) from the Pacific Ocean into the Pacific Arctic and the transformation processes occurring as the water transits both into the Arctic Ocean and east into the Canadian Arctic Archipelago (CAA) and to a limited extent, west into the East Siberian Sea (ESS). Available data indicate that the Chukchi Sea is the dominant PAR region for atmospheric carbon dioxide (CO_2) uptake, while the Beaufort Sea (BS) and CAA remove comparatively less CO_2, and the CAA and ESS are weak seasonal sources of CO_2. With the extensive reduction of sea ice in the deep Canada Basin (CB), CO_2 uptake has increased in the summer period. There is a small positive-sign export of DIC, indicating that the CB is a net heterotrophic system. The marginal seas can seasonally produce labile organic carbon from primary production and biological processing of carbon, riverine input and coastal erosion that are also recycled within and in transit out of the ecosystems, with the potential of a warming climate causing an increase in the production and export of DIC. Uncertainty remains as to whether a changing climate will make the PAR a sink or source of CO_2 in the future.

In Chap. 9, Mathis et al. (2014, this volume) discuss the chemical and biological components influencing the Arctic marine carbon cycle, including primary production, carbon transformations, and export production that are sensitive to sea ice loss, warming temperatures, changes in the timing and location of primary production, freshwater inputs, and ocean acidification. Seasonal variability in dissolved organic carbon (DOC) and particulate organic carbon (POC) production are key components of the marine carbon cycle, which vary with seasonal gradients in light, ice-cover and riverine input to the Arctic Ocean and to marginal seas. Secondary production and microbial processes in the water column, along with microbial processing in the underlying sediments, are key elements of the marine carbon cycle. Regions within the PAR are experiencing seasonal ocean acidification and decreasing pH. This is reducing the saturation states of calcium carbonate, which could have detrimental impacts on calcifying fauna, both in the water column and in sediments. Since these organisms are important prey for upper trophic level predators, additional studies of key biochemical and biological processes in the marine carbon cycle are necessary in a rapidly changing Arctic.

1.7 Lower and Upper Trophic Levels and Ecosystem Modeling

In Chap. 10, Nelson et al. (2014, this volume) evaluate the changes occurring in lower trophic level productivity, composition and biomass in the PAR, including northward range extensions of certain species. Variability in species composition can impact primary production, trophic connectivity and carbon cycling that influence ecosystem dynamics in the PAR. This chapter includes information on the distribution and abundance of microbes, zooplankton, and benthic organisms, including their potential response to increasing seawater temperature, freshwater content, lower pH, and changes in sea ice dynamics. Smaller organisms, such as microbes and microzooplankton, are most susceptible to environmental changes and are expected to respond at a faster rate. Changes in the species composition and productivity of benthic organisms in the PAR will affect the roles played by this diverse fauna in carbon cycling and as a prey items. Multidisciplinary studies of the linkages between lower tropic species ecology, physics and geochemistry are enhancing our understanding and capacity to predict the future status of PAR marine ecosystems during this period of rapid change.

In Chap. 11, Moore et al. (2014, this volume) provide an overview of the key components of upper trophic level groups, including fish, seabirds and marine mammals, which are top predators in the Arctic system. These organisms can respond to environmental variability and specific examples in this chapter outline species responses to ecosystem change. For example, some fish and snow crab are being found now further north in the PAR, while seabirds and marine mammals have changed their phenology and diet to respond to variability in sea ice and lower trophic level prey. Since migrating species have the ability to identify variation in dense prey, upper trophic level organisms can reflect ecosystem shifts by changing migration routes, abundance levels, diet, reproduction and body condition. Partnerships between local indigenous arctic residents and scientists are enhancing our understanding of the biophysical links between sea ice conditions and migrating species. Continued collaborations are an important need for understanding upper trophic level resources, habitat use and ecological relationships.

In Chap. 12, Deal et al. (2014, this volume) discuss ongoing and developing marine biogeochemical and ecosystem models in the PAR. This includes the complexities associated with different scales of modelling, from one-dimensional to regional and global Earth System scales, and combining physical forcing with biological and chemical processes. Models are being used to evaluate benthic, pelagic and sea ice impacts on ecosystem dynamics with the objective of building scenarios of ecosystem response to climate impacts. The authors highlight the importance of capturing the timing and location of the ice edge and open water blooms, including the subsurface chlorophyll maximum layer, for simulating the food web structure. Deal et al. emphasize the need for continued biogeochemical observations to use as input into modeling efforts that improve our understanding and forecasting of ecosystem dynamics for policy decision making.

1.8 Summary

The PAR is currently experiencing the largest sector changes in Arctic seasonal sea ice extent and thickness, but with different responses within the ecosystem. A challenge to both the modeling and observational community is to develop workable scenarios to investigate:

1. How will changes in the flow-through dynamics of what can be termed the Bering Strait continental shelf complex affect downstream Arctic ecosystems?
2. Will changes in the timing and extent of ice formation influence halocline formation and thickness, and if so, what are the ramifications of a reduction in the density gradients across the halocline?
3. Will an increase in freshwater and heat flux through Bering Strait move the PAR to a new stable state and what consequences would this have for the influence of

nutrients, heat, and freshwater on near-field (Pacific Arctic region) ecosystems and downstream (Arctic basin and Canadian Archipelago) ecosystems?
4. How will physical and biogeochemical fluxes vary in the Pacific Arctic Region in concert with lower latitude climate variability and change?

Determining the key drivers and responders to change in this region are essential in order to determine the downstream impacts on the Arctic system, including its connectivity to the world ocean. A hierarchy of models, including process, regional Arctic and global climate and Earth System scales (GC/ESMs) are needed to address these and other PAR related questions.

Early season ice retreat influences timing of the spring bloom and associated lower trophic level consumption of organic carbon. Changes will have cascading effects to benthos and higher trophic organisms. There are indications of increased freshwater flux and summer seawater temperatures, both that influence biological processes, and changes in the timing of productivity over the shelf and slope regions that will rapidly impact trophic structure and carbon transport from shelf to basin. Sea-ice free areas will allow for biological northward expansion of fish, but could have negative impacts on competing, benthic-feeding marine mammals. Impacts on marine mammals harvested for subsistence could also be affected.

The need remains for pan-Arctic comparative studies with standardized data collections to allow compare/contrast evaluations and projection of various scenarios of Arctic change. Ultimately, the need is to determine whether observed changes are due to climate warming or natural variability. These research needs are best met by collection of long-term time-series data at key select sites, integrated with relevant process and coupled modeling studies. Newly evolving programs, such as the Distributed Biological Observatory (Grebmeier et al. 2010) will help to fill these observational gaps, but could be supplemented with efforts in different regions, seasons and climate regimes.

Modelling approaches discussed in this volume renew a call for process-level understanding of the coupled Arctic climate system and improved modeling capabilities to advance knowledge and prediction of climate change in the Pacific Arctic. There is a clear need for eddy-resolving, coupled physical and biogeochemical modeling capabilities. Success with these approaches will lead to better understanding of critical physical processes, potential feedbacks between them and their overall impact of the whole ecosystem. Current global models still have significant limitations with regard to representing the Pacific Arctic. In particular, challenges are associated with representing processes, such as surface mixed layer, eddies, cold halocline, seasonal pycnocline, near surface temperature maximum as well as sea ice thickness distribution, deformation and drift. Regional climate system models, with high spatial and temporal resolution and focus on the Arctic or Pacific Arctic region are key requirements (Maslowski et al. 2012). An Arctic System Model (ASM) should readily allow addition of new system components, such as marine biogeochemistry, ice-sheet/ocean interaction, etc. A fully coupled ASM should allow resolving processes and feedbacks between them. Along with the development of ASMs, observations to constrain and evaluate them are as critical.

Acknowledgements We thank the co-authors of this special synthesis activity for their time and effort in developing the scientific products for this volume. We especially thank Dr. John Calder for his continuous support of the Pacific Arctic Group synthesis activities through the Arctic Research Program of the US National Oceanic and Atmospheric Administration (NOAA). In addition, we thank our international colleagues in the PAG for their continued collaboration in research activities and the support of their managers. We thank Lee Cooper for his editorial efforts on the dedication and introductory chapter. Financial support related to this special synthesis volume was provided to JM Grebmeier (NOAA grant # NA09OAR4310092) and W Maslowski by the DOE Regional and Global Climate Modeling and NSF Office of Polar Programs.

References

Arrigo KR, Perovich DK, Pickart RS, Brown ZW, Van Dijken G, Lowry KE, Mills MM, Palmer M, Balch W, Bahr F, Bates N, Benitez-Nelson C, Bowler B, Brownlee E, Ehn JK, Frey KE, Garley R, Laney SR, Lubelczyk L, Mathis J, Matsuoka A, Mitchell BG, Moore GWK, Ortega-Retuerta E, Pal S, Polashenski CM, Reynolds R, Schieber B, Sosik H, Stephens M, Swift JH (2012) Massive phytoplankton blooms under Arctic sea ice. Science 336:1408

Ashjian CJ, Braund SR, Campbell RG, George JC, Kruse J, Maslowski W, Moore SE, Nicolson CR, Okkonen SR, Sherr BF, Sherr EB, Spitz Y (2010) Climate variability, oceanography, bowhead whale distribution, and Iñupiat subsistence whaling near Barrow AK. Arctic 63:179–194

Berchok CL, Clapham PJ, Crance JL, Moore SE, Napp J, Overland J, Wang M, Stabeno P, Guerra M, Clark CW (2014) Passive acoustic detection and monitoring of endangered whales in the Arctic (Beaufort, Chukchi) & Ecosystem observations in the Chukchi Sea: biophysical moorings and climate modeling. 2013 Annual Report, BOEM/NOAA Interagency Agreement Number M09PG00016. National Marine Mammal Laboratory, Alaska Fisheries Science Center, NOAA, 14 p

Bluhm BA, Iken K, Hopcroft RR (2010) Observations and exploration of the Arctic's Canada Basin and the Chukchi Sea: the Hidden Ocean and RUSALCA expeditions. Deep-Sea Res 57:1–4

Cai W-J, Guo L, Grebmeier JM, Chen L, Zhang H (2012) Biogeochemical studies from the Chinese National Arctic Research Expeditions. Deep-Sea Res 81–84:1–2

Cai W-J, Bates NR, Guo L, Anderson LG, Mathis JT, Wanninkhof R, Hansell DA, Chen L, Igor Semiletov IP (2014) Chapter 8: Carbon fluxes across boundaries in the Pacific Arctic region in a changing environment. In: Grebmeier JM, Maslowski W (eds) The Pacific Arctic region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht, pp 199–222

Carmack EC, McLaughlin FA, Vagle S, Melling H, Williams WJ (2010) Structures and property distributions in the three oceans surrounding Canada in 2007: a basis for a long-term ocean climate monitoring strategy. Atmos Ocean 48:211–224

Clement Kinney J, Maslowski W, Aksenov Y, de Cuevas B, Jakacki J, Nguyen A, Osinski R, Steele M, Woodgate RA, Zhang J (2014) Chapter 7: On the flow through Bering Strait: a synthesis of model results and observations. In: Grebmeier JM, Maslowski W (eds) The Pacific Arctic region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht, pp 167–198

Comiso JC (2012) Large decadal decline of the Arctic multiyear ice cover. J Clim 25:1176–1193

Cooper LW, Whitledge TT, Grebmeier JG, Weingartner T (1997) Nutrient, salinity and stable oxygen isotope composition of Bering and Chukchi Sea in and around the Bering Strait. J Geophys Res 102:12563–12574

Day RH, Weingartner TJ, Hopcroft RR, Aerts LAM, Blanchard AL, Gall AE, Gallaway BJ, Hannay DE, Holladay BA, Mathis JT, Norcross BL, Questel JM, Wisdom SS (2013) The offshore northeastern Chukchi Sea: a complex high-latitude system. Cont Shelf Res 67:147–165

Deal CJ, Steiner N, Christian J, Clement Kinney J, Denman K, Elliott S, Gibson G, Meibing J, Lavoie D, Lee S, Lee W, Maslowski W, Wang J, Watanabe E (2014) Chapter 12: Progress and challenges in biogeochemical modeling of the Pacific Arctic region. In: Grebmeier JM, Maslowski W (eds) The Pacific Arctic region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht, pp 393–446
Dunton KE, Grebmeier JM, Trefry JH (2014) The benthic ecosystem of the northeastern Chukchi Sea: an overview of its unique biogeochemistry and biological characteristics. Deep-Sea Res II 102:1–8
Frey KE, Maslanik JA, Clement Kinney J, Maslowski W (2014) Recent variability in sea ice cover, age, and thickness in the Pacific Arctic region. In: Grebmeier JM, Maslowski W (eds) The Pacific Arctic region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht, pp 31–64
Grebmeier JM (2012) Shifting patterns of life in the Pacific Arctic and Sub-Arctic seas. Annu Rev Mar Sci 4:63–78
Grebmeier JM, Cooper LW, Feder HM, Sirenko BI (2006a) Ecosystem dynamics of the Pacific-influenced Northern Bering and Chukchi seas in the Amerasian Arctic. Prog Oceanogr 71:331–361
Grebmeier JM, Overland JE, Moore SE, Farley EV, Carmack EC, Cooper LW, Frey KE, Helle JH, McLoughlin FA, McNutt L (2006b) A major ecosystem shift observed in the northern Bering Sea. Science 311:1461–1464
Grebmeier JM, Moore SE, Overland JE, Frey KE, Gradinger R (2010) Biological response to recent Pacific Arctic sea ice retreats. EOS Trans Am Geophys Union 91(18):161–162
Maslowski W, Clement Kinney J, Higgins Roberts AF (2012) The future of Arctic sea ice. Annu Rev Earth Planet Sci 40:625–654
Maslowski W, Clement Kinney J, Okkonen SR, Osinski R, Roberts AF, Williams W (2014) Chapter 5: The large scale ocean circulation and physical processes controlling Pacific-Arctic interactions. In: Grebmeier JM, Maslowski W (eds) The Pacific Arctic region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht, pp 101–132
Mathis JT, Hansell DA, Kadko D, Bates NR, Cooper LW (2007) Determining net dissolved organic carbon production in the hydrographically complex western Arctic Ocean. Limnol Oceanogr 52:1789–1799
Mathis JT, Grebmeier JM, Hansell DA, Hopcroft RR, Kirchman DL, Lee SH, Moran SB, Bates NR, VanLaningham S, Cross JN, Cai W-J (2014) Chapter 9: Carbon biogeochemistry of the western Arctic: primary production, carbon export and the controls on ocean acidification. In: Grebmeier JM, Maslowski W (eds) The Pacific Arctic region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht, pp 223–268
Moore SE (2008) Marine mammals as ecosystem sentinels. J Mammal 89(3):534–540
Moore SE, Grebmeier JM, Davies JR (2003) Gray whale distribution relative to forage habitat in the northern Bering Sea: current conditions and retrospective summary. Can J Zool 81:734–742. doi:10.1139/Z03-043
Moore SE, Logerwell E, Eisner L, Farley E, Harwood L, Kuletz K, Lovvorn J, Murphy J, Quakenbush L (2014) Chapter 11: Marine fishes, birds and mammals as sentinels of ecosystem variability and reorganization in the Pacific Arctic region. In: Grebmeier JM, Maslowski W (eds) The Pacific Arctic region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht, pp 337–392
Nelson RJ, Ashjian C, Bluhm B, Conlan K, Gradinger R, Grebmeier J, Hill V, Hopcroft R, Hunt B, Joo H, Kirchman D, Kosobokova K, Lee S, Li WKW, Lovejoy C, Poulin M, Sherr E, Young K (2014) Chapter 10: Biodiversity and biogeography of the lower trophic taxa of the Pacific Arctic region: sensitivities to climate change. In: Grebmeier JM, Maslowski W (eds) The Pacific Arctic region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht, pp 269–336
Overland JE, Stabeno PJ (2004) Is the climate of the Bering Sea warming and affecting the ecosystem? Eos Trans Am Geophys Union 85:309–316