PICES SPECIAL PUBLICATION 7

Marine Ecosystems of the North Pacific Ocean 2009–2016: Synthesis Report

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Marine Ecosystems of the North Pacific Ocean 2009–2016: Synthesis Report

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Please cite this publication as:

Chandler, P.C. and Yoo, S. [Eds.] 2021. Marine Ecosystems of the North Pacific Ocean 2009–2016: Synthesis Report, PICES Special Publication 7, 82 pp.

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Published by:

North Pacific Marine Science Organization (PICES)
c/o Institute of Ocean Sciences
P.O. Box 6000
Sidney, BC, Canada V8L 4B2

www.pices.int

Project Designer:

Lori Waters
Waters Biomedical Communications
Victoria, BC, Canada

ISSN: 1813-8519
ISBN: 978-1-927797-41-9
ISBN (Web version): 978-1-927797-42-6

Front cover images: Top: Southern resident killer whales. Credit: Brianna Wright. Bottom: Tide pool near Bamfield Marine Science Centre. Credit: Lori Waters. **Back cover image:** Eagle River sockeye salmon. Credit: Shane Kalyn.

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Participants at the NPESR3 Synthesis Workshop, Yokohama, Japan, April 2019. Back: Sinjae Yoo, Peter Chandler, Sonia Batten, Matt Baker, Elizabeth Siddon, Vyacheslav Lobanov, Kazuaki Tadokoro; Front: Stephani Zador, Tsuneo Ono, Kirill Kivva, Jeanette Gann.

Foreword

In an era of increasing anthropogenic stressors on the ocean and changing climate conditions, timely and audience-focused environmental status reports are important for the proper stewardship and management of the world's oceans. Responding to this need, PICES embarked on preparing an ecosystem status report aimed at informing the state and trend of North Pacific ecosystems back in 2001. PICES is uniquely situated as an international organization to assess the status of the North Pacific; as such, the production of timely status reports on the marine ecosystems of the North Pacific has been and continues to be a high PICES priority.

PICES scientists from Canada, Japan, the People's Republic of China, the Republic of Korea, the Russian Federation, and the United States of America produced two previous North Pacific Ecosystem Status Reports, in 2004 and 2010. Thus this series covers a time span stretching more than a quarter century. These are hard-copy reports (PICES Special Publications 1 and 4), which are also available in PDF format on the PICES website[1].

This third North Pacific Ecosystem Status Report (NPESR3) focuses on the time period 2009–2016 and includes PDF reports for each of the 14 PICES biogeographical regions in the North Pacific, and additional chapters examining climate and human dimensions. Based on these regional chapters, this Synthesis Report summarizes the ecosystem status for the entire North Pacific.

Recognizing the significant effort involved in producing the previous North Pacific Ecosystem Status Reports, PICES Working Group on the Third North Pacific Ecosystem Status Report (WG 35) implemented a new approach to streamline access to the diversity of information relevant to producing NPESR3. A web-based system to submit and archive Ecosystem Time Series Observations (ETSOs) was designed to facilitate access to data by report authors and to provide an archive of data used in the report. Nonetheless, considerable effort was still required and much appreciation is due to the remarkable Lead Authors: Matt Baker, Sonia Batten, Nick Bond, Keith Criddle, Fei Yu, Jeanette Gann, Steve Kasperski , Kirill Kivva, Hiroshi Kuroda, Vyacheslav Lobanov, Tsuneo Ono, Ivonne Ortiz, Elizabeth Siddon, Bill Sydeman, Kazuaki Tadokoro, Sinjae Yoo, Stephani Zador, and Yury Zuenko. Jeanette Gann was also responsible for managing the ETSOs and Lori Waters for designing this PICES Special Publication.

PICES Ecosystem Status Reports provide an important record of our understanding of conditions in the North Pacific for the specific time periods of interest. However, the rate at which ecosystem conditions are changing, and the ever-increasing volume of data being collected, raises the consideration of PICES providing annual ecosystem status reports. Whatever their format, future PICES reports will continue to advance scientific knowledge about the ocean environment and climate change, living resources and their ecosystems, and the impacts of human activities.

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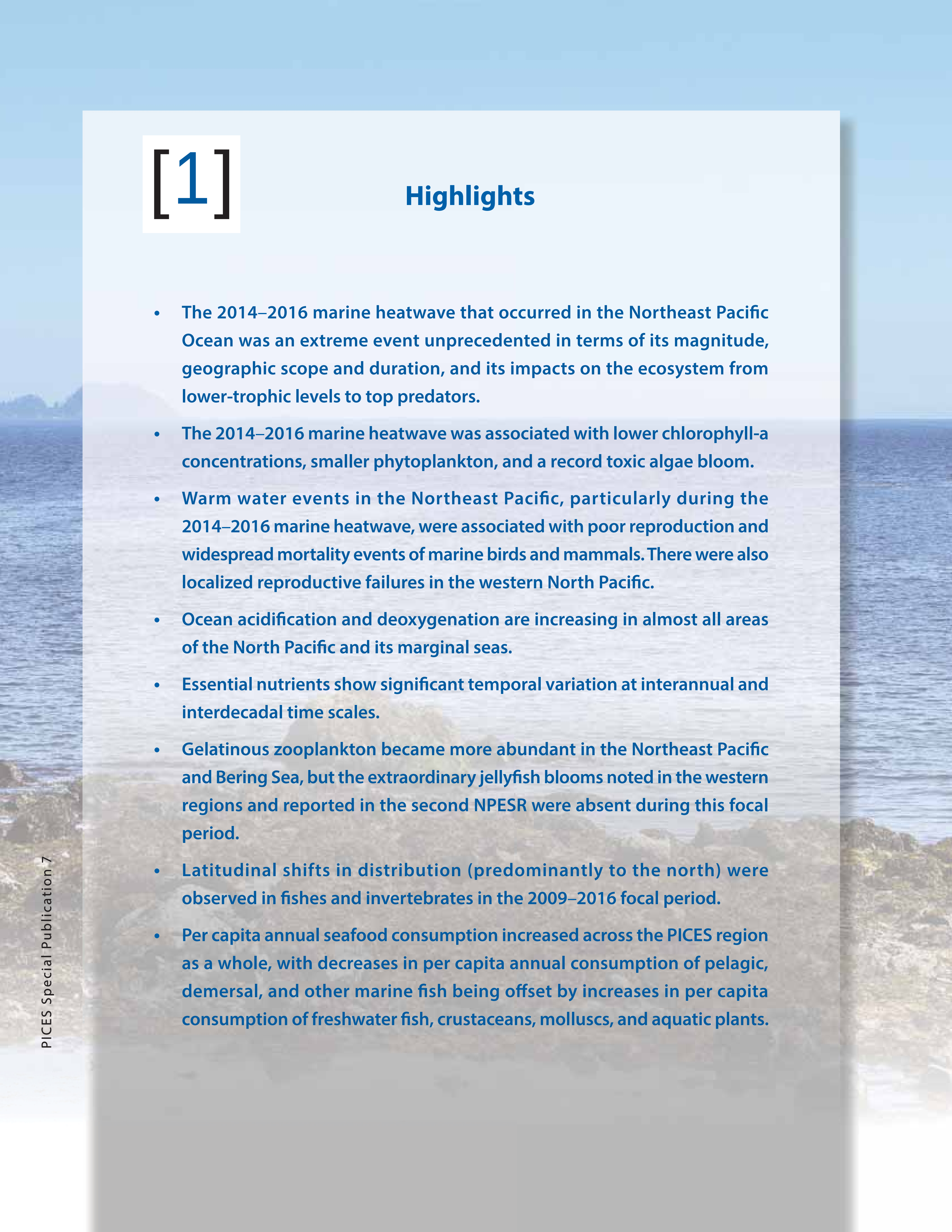
[1] https://meetings.pices.int/publications/special-publications/NPESR/2021



[1]

Highlights

- The 2014–2016 marine heatwave that occurred in the Northeast Pacific Ocean was an extreme event unprecedented in terms of its magnitude, geographic scope and duration, and its impacts on the ecosystem from lower-trophic levels to top predators.
- The 2014–2016 marine heatwave was associated with lower chlorophyll-a concentrations, smaller phytoplankton, and a record toxic algae bloom.
- Warm water events in the Northeast Pacific, particularly during the 2014–2016 marine heatwave, were associated with poor reproduction and widespread mortality events of marine birds and mammals. There were also localized reproductive failures in the western North Pacific.
- Ocean acidification and deoxygenation are increasing in almost all areas of the North Pacific and its marginal seas.
- Essential nutrients show significant temporal variation at interannual and interdecadal time scales.
- Gelatinous zooplankton became more abundant in the Northeast Pacific and Bering Sea, but the extraordinary jellyfish blooms noted in the western regions and reported in the second NPESR were absent during this focal period.
- Latitudinal shifts in distribution (predominantly to the north) were observed in fishes and invertebrates in the 2009–2016 focal period.
- Per capita annual seafood consumption increased across the PICES region as a whole, with decreases in per capita annual consumption of pelagic, demersal, and other marine fish being offset by increases in per capita consumption of freshwater fish, crustaceans, molluscs, and aquatic plants.

Chapter 1: Introduction

Authors: Peter C. Chandler and Sinjae Yoo

This is the third in a series of North Pacific Ecosystem Status Reports (NPESR) produced by the North Pacific Marine Science Organization (PICES), and is commonly referred to as NPESR3. The purpose of this synthesis report is to provide an integrated view of the status and trends in North Pacific marine ecosystems, and the vulnerability and resilience of these ecosystems to pressures from climate change and human activities. The intended audience includes those interested in the science of climate and marine ecosystems of the North Pacific Ocean, and the governments that deal with issues of policy and management of North Pacific ecosystems.

Coordinated by the Working Group on the Third North Pacific Ecosystem Status Report (WG 35), and based on the submissions of PICES scientists and their colleagues, the information presented offers an ecosystem-based understanding of the biological and physical environments, and an introduction to the human dimensions that shape and are shaped by these ecosystems.

The PICES region of interest includes the Pacific Ocean and adjacent seas north of 25°N, an area of over 35 million km^2. Based on the Large Marine Ecosystem boundaries defined by Sherman and Hempel (2009), the North Pacific has been divided into 14 regions characterized by distinct bathymetry, hydrography, productivity, and populations linked by trophic dependence (Figure 1-1). The naming convention for the NPESR3 regions was endorsed by the PICES Science Board and approved by Governing Council at PICES-2016[1]. Consistent with previous marine ecosystem status reports produced by PICES, the third edition consists of reports for each region and this synthesis report that addresses ecosystem status and trends for the entire North Pacific Ocean.

Each of the regional reports, as well as the reports on climate and human dimensions, were prepared under the guidance and supervision

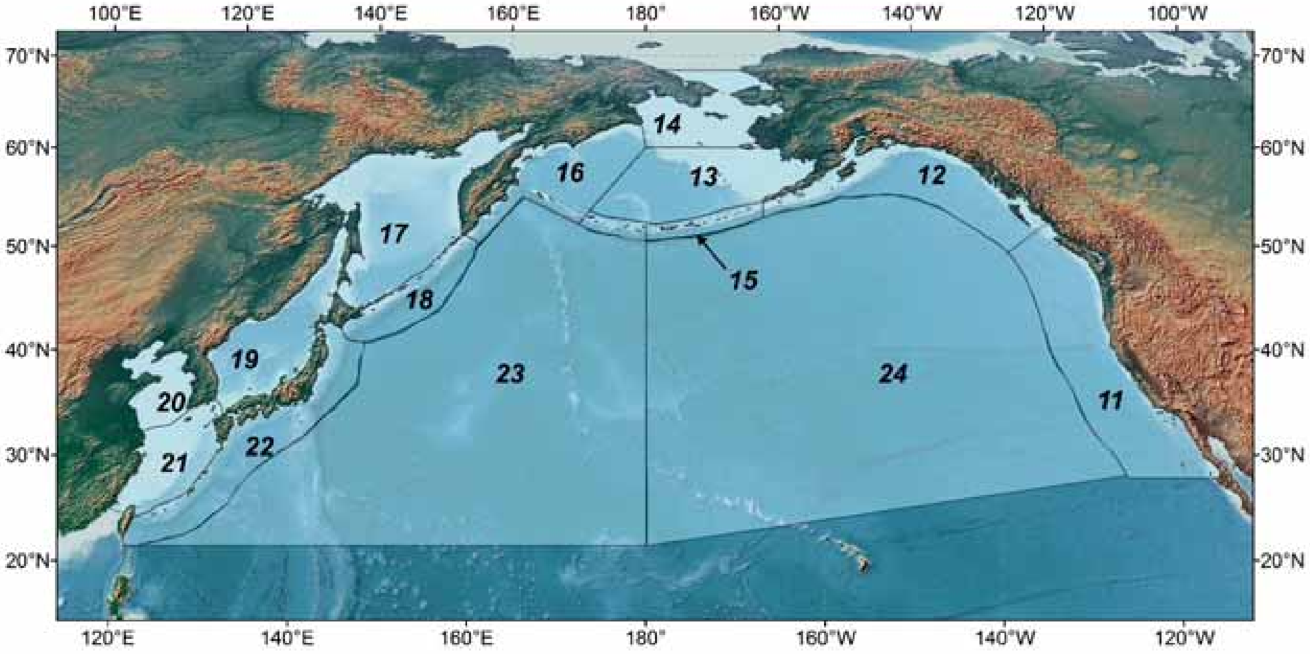


Figure 1-1. Map showing PICES division of the North Pacific into 14 regions.

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[1] https://meetings.pices.int/publications/annual-reports/2016/2016-GC-Decisions- San-Diego.pdf

of a Lead Author. For each region a common format was followed to describe the physical and chemical oceanography, as well as the biological oceanography of phytoplankton, zooplankton, fishes and invertebrates, marine birds and mammals. Depending on the information available, regional reports also included sections on benthos, biogenic habitat, and pollution. The Climate section examines the atmosphere–ocean system of the entire North Pacific and the Human Dimensions section addresses how biophysical changes impact the well-being of people, communities, and economies.

The time period of focus for this report is 2009–2016. As with previous NPESR reports, the analyses and descriptions of observations within the focal period are interpreted in the context of historical data and more recent events.

Climate change, ecosystem considerations and emerging issues

The state of the North Pacific Ocean, as with other regions of the globe, is influenced by the cumulative effects of seasonal and inherent, essentially chaotic, variability and by anthropogenically-caused climate change. These effects are observed throughout the world as increasing air and ocean temperatures, declining sea ice extent, rising sea levels, shifting species distributions, and more frequent extreme events. While the rates of change vary from one indicator to another and from one region to another, the overall direction of change is consistent with a warming climate that is expected to continue for many decades. Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. These climate changes have had widespread impacts on human and natural systems (IPCC, 2014).

Ocean temperature is an important environmental indicator because it influences physical processes such as mixing and sea ice formation, chemical processes such as deoxygenation, and the condition and behaviour of species that live in the ocean. Sea surface temperature (SST) is an effective indicator of long-term change because direct observations have been made for over 100 years. Figure 1-2 shows the annual changes in SST averaged over the North Pacific Ocean over the last 100 years as the anomaly from the 100-year mean value; also shown is the trend line that best fits the data. The SST data show above-average conditions since 1990, and a trend towards increased warming in the future. There was a significant and sustained temperature increase in 2014, about midway through the 2009–2016 focal period.

A marine heatwave occurred in the Northeast Pacific Ocean during 2014–2016, and might even be considered to have continued in the Bering Sea into 2019. This was an extreme event that was unprecedented in terms of its magnitude, geographic scope and duration,

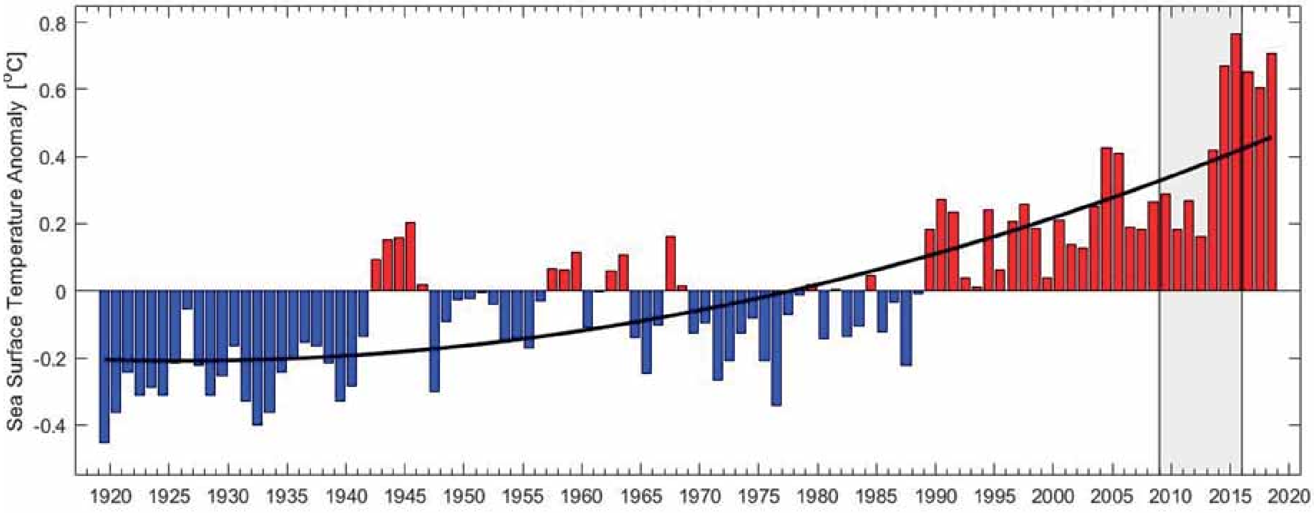
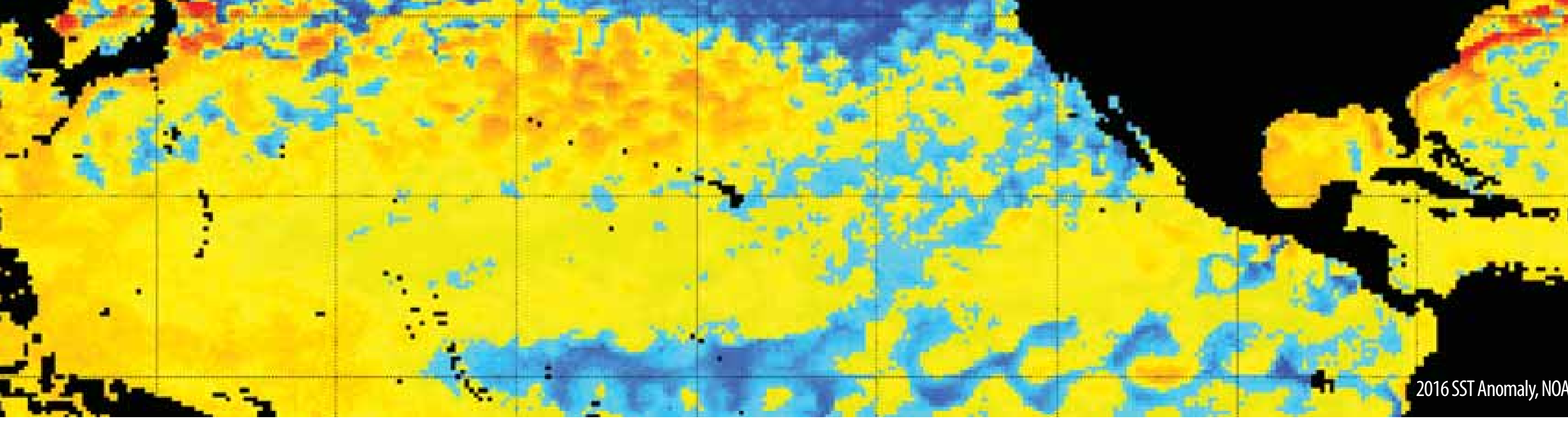


Figure 1-2. Time series of sea surface temperature (as the anomaly from the long-term average conditions) as provided by the NOAA/OAR/ESRL Physical Sciences Laboratory, Boulder, Colorado, USA, https://www.esrl.noaa.gov/psd/. Curved line shows trend towards increased warming. Grey shaded area is the focal period of this report.



2016 SST Anomaly, NOA

and impacts on the marine ecosystem. Given the rates of warming indicated by climate model simulations, "normal" upper ocean temperatures during the middle of the 21st century will be comparable to those that were attained during this recent event. It remains an open question the extent to which the ecosystem responses to slow warming will resemble those that were associated with this past marine heatwave. It is very likely there will be more heat waves in the future associated with large and disruptive biological responses and transitions in the structure, diversity, and function of marine ecosystems.

Climate change is likely to bring a poleward shift in the belt of westerly winds over the western and central North Pacific Ocean (Yang et al., 2016). This shift may be obscured during roughly the next 20–30 years by the internal variability of the North Pacific climate on multi-year time scales (Seager and Simpson, 2016). The shifting north–south position of the jet stream causes profound north–south contrasts in the Kuroshio/Oyashio ecosystem, including commercially-valuable fish populations (Yatsu et al., 2013). It is hoped that improved understanding of the dynamics controlling this region's response to climate change will be forthcoming.

The impacts of global warming are clearly evident in the high-latitude region of Alaska, and the changes that have occurred in the northern Bering Sea have been particularly striking. In the past historical record, this region was subject to 5–6 months of sea ice each year, even during warm periods for the North Pacific Ocean in an overall sense. Recently this has no longer been the case, with 3 out of the 4 winters from 2015 through 2018 featuring greatly reduced ice cover (Stabeno et al., 2018), continuing into 2019. An important factor appears to be conditions in the Chukchi Sea north of the Bering Sea, where sea ice is developing later in the fall. Postponement in the development of sea ice in the Chukchi Sea results in late arrival of sea ice in the Bering Sea. Unless there is persistently cold weather, the consequence is less ice for the Bering Sea for the winter season as a whole. The implications for the marine ecosystem include changes in lower-trophic community structure, notably a reduction in ice algae, and a tendency for greater pelagic productivity at the expense of the benthos. The overall warming observed for the Bering Sea, in turn, has served to warm the Chukchi Sea, the latter of which is subject to northward flow through the Bering Strait in the summer as well as central Arctic influences.

There is growing interest in determining the predictability of the physical processes of the North Pacific Ocean, including associated biological responses, on time scales of months to years. The models that are used for this purpose generally resemble those used to simulate the effects of climate change. Skillful forecasts would be of considerable value for management and other interests, of course, but there are additional, indirect benefits. The process of developing, evaluating, and improving forecast systems can provide important insights into the key processes controlling physical, chemical, and biological ocean properties.

Real-time prediction systems able to forecast several months have been created and tested for a number of regions and ecosystem applications. A list of these efforts was included in Payne et al. (2017); more are in various stages of development. It bears emphasizing that there are real limits to predictability, in part because of the inherent uncertainty in the climate forcing and hence future atmospheric and physical oceanographic conditions. Additional errors are introduced in the modelling of biological responses, whether using empirical/statistical relationships or dynamical downscaling with high-resolution numerical ocean models incorporating biogeochemical processes (e.g., Siedlecki et al., 2016). The results from these sorts of forecast systems are largely experimental and are just


Tamara Fraser

beginning to be used for tactical management purposes. A review of the road ahead is provided by Payne et al. (2017)

The potential predictability of various properties of the North Pacific on multi-year time scales is of considerable interest. It turns out that there are slow oceanic processes, such as westward-propagating Rossby waves, that may be able to be exploited for making extended predictions. The promise, and pitfalls, of these kinds of predictions are in the process of being examined. A leading role in this effort is being carried out by the PICES Working Group on Climate and Ecosystem Predictability (WG 40)[2].

Evidence of a changing climate seen in the SST record is consistent with changes in other ocean and ecosystem indicators, such as sea level rise, the loss of sea ice, and the presence of warm water species in normally cool water locations. During the focal period of this report, other issues have emerged, such as the increase in microplastic pollution, the ecosystem consequences of the 2011 Tohoku earthquake and tsunami off the east coast of Japan, and the increased awareness of the importance of human dimensions in describing the status of the North Pacific.

The extreme climate events linked to marine bird die-offs highlight a potential shortage and/or change in the availability of typical planktonic and piscivorous prey of marine birds and mammals. Bird die-offs have broadened from species-specific and localized events to those impacting birds at the family-level, affecting species with different foraging strategies and prey over a wider area, and more often. Changes in the spatial distribution of marine mammals, along with die-offs are creating new interactions with humans, including sightings of species that were previously rare or infrequent, as well as high visibility of dead animals on beaches and ensuing cleanup activities.

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[2] https://meetings.pices.int/members/working-groups/wg40

Breakout Box

Marine debris in the North Pacific Ocean

Author: Cathryn Clarke Murray

Marine debris has become a significant concern for the health of the ocean and is increasing in magnitude. Marine debris has had adverse impacts on pelagic and coastal ecosystems and the various ecosystem services they provide (Gall and Thompson, 2015). The primary impact of marine debris on marine birds and mammals and sea turtles through entanglement and ingestion is well documented (Laist 1997; Gall and Thompson, 2015) and the impact of microplastics (plastics less than 5 mm in diameter) on marine ecosystems has become an emerging concern (Andrady, 2011; Wright et al., 2013). In addition, marine debris provides new habitat and facilitates the transport of invasive species (Gall and Thompson, 2015), as highlighted by the transport of coastal Japanese species to North America by debris from the Great East Japan Earthquake and tsunami of 2011 (Carlton et al., 2017).

Debris is most visible and noticeable where it washes up on shorelines. It has been documented throughout the North Pacific: the United States Pacific coast and Hawaii (Ribic et al., 2012), northwestern Hawaiian Islands (Morishige et al., 2007), Maui, Hawaii (Blickley et al., 2016), and northern Japan (Goto and Shibata, 2015). Marine debris originating from both land and sea-based sources of the world could increase monotonously each year, corresponding to global plastic production (Jambeck et al., 2015).

In 2011 an estimated 5 million tons of debris washed into the Pacific Ocean, initiated by the tsunami generated from the Great East Japan Earthquake (Ministry of Environment, Japan, 2012). This single event delivered an amount in the range of the estimated global debris input to the ocean each year (4.8 to 12.7 million metric tons) (Jambeck et al., 2015). The debris landings after 2013 were significantly different than those prior to 2012 (Figure 1, Clarke Murray et al., 2018) with an almost 10-fold increase in debris influx to sites in northern Washington State over that recorded in the 9-year period prior to the tsunami event.

The total amount of debris arriving monthly to actively monitored North American coastlines in the post-tsunami months ranged from 150 to 1,951 items, and the cumulative arrival of documented debris items on the coastlines of PICES regions 11 and 12 was more than 93,000 items (Figure 2, Clarke Murray et al., 2018).

There was a significant increase in debris from baseline levels recorded on the west coast of North America and Hawaii in the years following the Great Japan Tsunami of 2011 and this unique and unprecedented mega-pulse debris event elevated the global issue of marine debris. Recent research demonstrated debris has the potential to transport non-native species to new shorelines, adding to the known impacts that marine debris may have on the world's oceans.

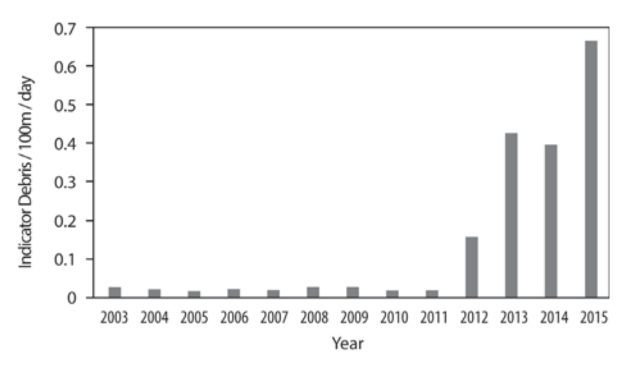

Figure 1. Mean yearly debris influx of indicator items from 2003 to 2015 at sites in northern Washington State. Adapted from Clarke Murray et al. (2018).

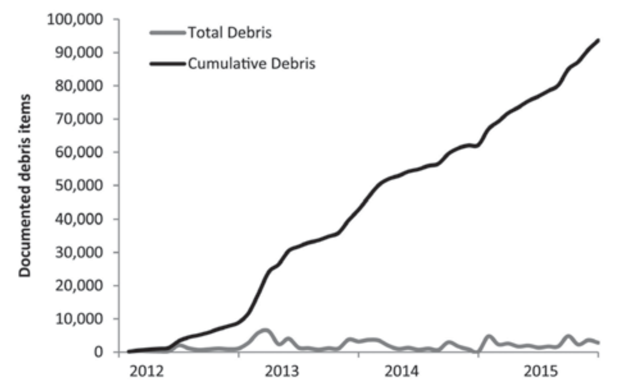

Figure 2. Total (grey) and cumulative (black) number of documented debris items arriving to monitored shoreline sites (excluding Hawaii) over time (2012–2015). Adapted from Clarke Murray et al. (2018).

US Navy

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NOAA

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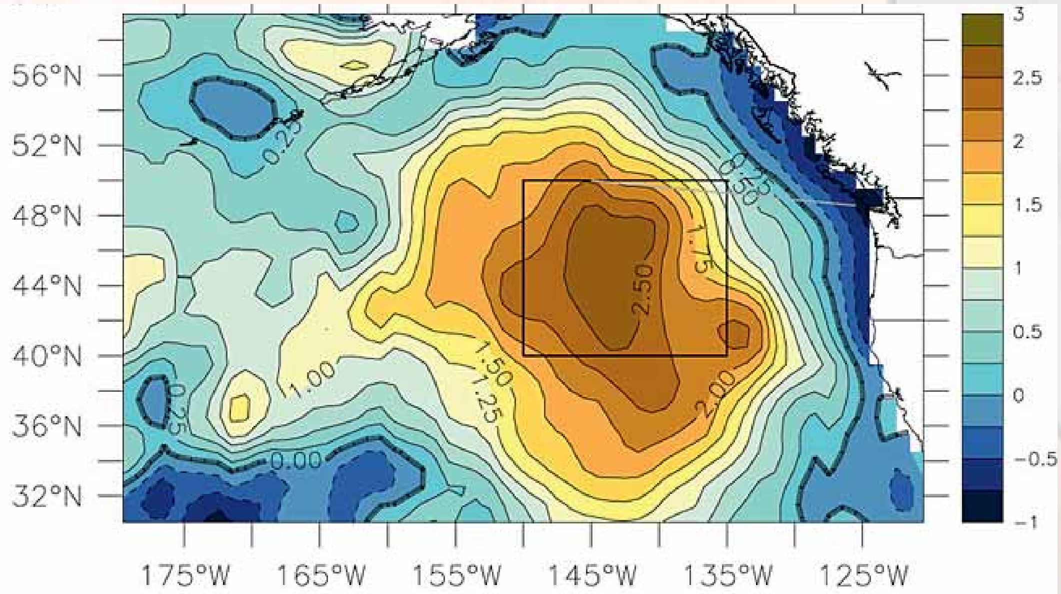
[2]

Highlight

- **In the 2009–2016 focal period, there was considerable interannual variability associated with El Niño/La Niña, but the dominant signal, perhaps indicative of future climate change scenarios, was the 2014–2016 marine heatwave.**



Sea surface temperature anomalies (°C) in the Northeast Pacific Ocean for February 2014. Anomalies are calculated relative to the mean from 1981 to 2010. From Bond et al. (2015)[1].

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[1] Bond, N.A., Cronin, M.F., Freeland, H., Mantua, N. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters 42: 3414–3420.

Chapter 2: Climate

Author: Nicholas A. Bond

Introduction

In the context of what we know about the climate system, scientific consensus exists that global climate change is affecting many parts of the North Pacific Ocean. These effects appear especially prominent at higher latitudes; at lower latitudes climate variability generally still dominates systematic long-term changes. The intrinsic and extrinsic sources of climate variability are difficult to separate, complicating interpretation of trends and attribution. The American Meteorological Society has produced a special volume of the Bulletin of the American Meteorological Society on "The State of the Climate" for each of the years from 2009 through 2016; these volumes provide a wealth of information on atmospheric and oceanic conditions during the period of interest.

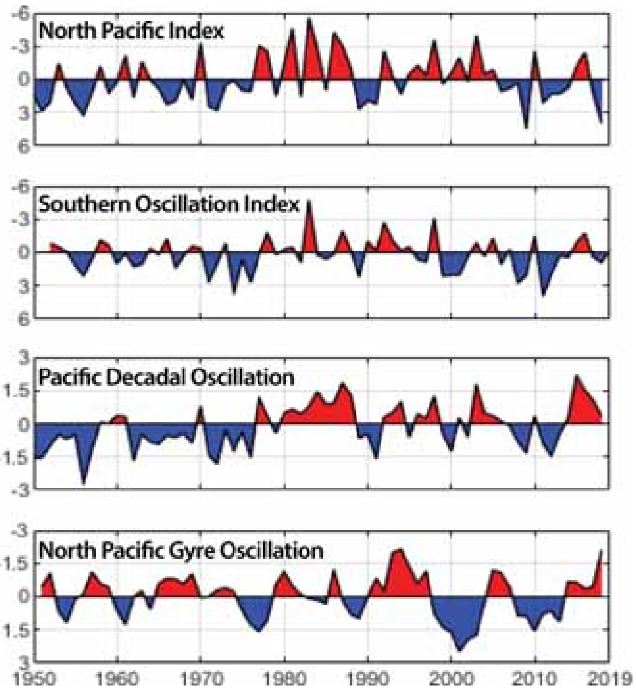


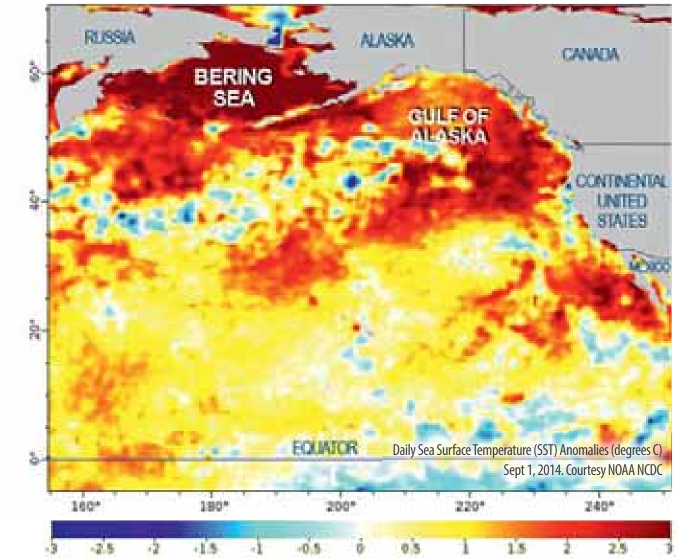
Figure 2-1. Time series of Pacific Ocean climate indices averaged over the months of November, December, January, February, and March. Some series are inverted (negative values are above the axes) so that all series are red when northeastern Pacific ocean temperatures are anomalously warm.

Broadly speaking, much of the relevant research on the climate of the North Pacific near the end of the 20th century focused on documenting the principal patterns of variability (e.g., the Pacific Decadal Oscillation or PDO, see Figure 2-1) and their causes. For a variety of applications, simple indices of these patterns or modes were found to correspond significantly with biological variables. Recent studies have indicated that these relationships may be less robust than first appeared (and hoped). This is not really unexpected in that it has always been recognized that the North Pacific is subject to multiple factors spanning a wide range of spatial and temporal scales, and hence is a very complex system.

The climate of the North Pacific Ocean can be considered as two seasons: a cool season defined as the months of November through March during which the ocean is generally losing heat to the atmosphere and the upper mixed layer is relatively deep, and a warm season defined as the months of May through September when the upper ocean is gaining heat, and the mixed layer is shallow.

Recent variability

During the boreal winter of 2009–2010 a moderate El Niño developed coinciding with a relatively strong (lower than normal) sea level pressure (SLP) and southeast displaced Aleutian low, leading to anomalous winds from the south (downwelling favorable) along the west coast of North America. The tropical Pacific experienced cooling in the following boreal spring of 2010 resulting in moderate La Niña conditions that prevailed from late 2010 into 2012. The Aleutian low, as reflected in the North Pacific Index (NPI), was weaker than normal during the winter of 2010–2011 and to a lesser extent, during the winter of 2011–2012. As is often the case during periods of La Niña, negative PDO conditions were present with cooler than normal sea surface temperatures (SSTs) in a band along the west coast of North America, and warmer than normal SSTs in the central North Pacific.



Daily Sea Surface Temperature (SST) Anomalies (degrees C)
Sept 1, 2014. Courtesy NOAA NCDC

In 2014 the upper ocean heat content in the tropical Pacific became considerably greater than normal, resulting in climate model predictions for a major El Niño during the winter of 2014–2015. A very strong El Niño did occur, but its onset was not until the summer of 2015. Nevertheless, the winters of 2014–2015 and 2015–2016 both featured relatively strong Aleutian lows. This distribution of anomalous SLP brought about cyclonic wind anomalies in PICES regions 11, 12 and 24 during both winters, resulting in anomalous downwelling in the coastal zone and upward Ekman pumping farther offshore. These years also marked a shift to the strongly positive sense of the PDO.

The marine heatwave that occurred in the Northeast Pacific Ocean during 2014–2016 was an extreme event unprecedented in terms of its magnitude, geographic scope, and duration and its impacts on the ecosystem from lower-trophic levels to top predators. Its development can be attributed to a combination of unusual and persistent weather patterns due to internal variability and long-term warming due to climate change (Jacox et al., 2018; Walsh et al., 2018). Given the rates of warming indicated by climate model simulations, "normal" upper ocean temperatures during the middle of the 21st century will be comparable to those that were attained during this recent event.

El Niño–Southern Oscillation and the Aleutian low

The correspondence between the state of El Niño–Southern Oscillation (ENSO) and the Aleutian low is a central tenet of North Pacific climate variability. Warm events in the tropical Pacific (El Niños) during winter generally result in stronger mean Aleutian lows that are displaced to the southeast, and their counterparts (La Niñas) with weaker Aleutian lows. This relationship is considered responsible for much of the predictability in the North Pacific atmosphere and ocean on seasonal time horizons, and is illustrated in Figure 2-1 using the Southern Oscillation Index (SOI) to characterize ENSO, with negative values signifying warm events, and the North Pacific Index (NPI) to characterize the Aleutian low, with negative values signifying lower than normal pressures. A number of studies in the previous 10–15 years, as reviewed by Capotondi et al., (2015), have revealed that there is substantial diversity in the nature and not just amplitude of ENSO events. Much of this work has focused on the differences between central and eastern Pacific El Niños, and the differences in their associated teleconnections to weather patterns over the North Pacific and North America. Di Lorenzo and co-authors have shown that the central Pacific events tend to project on the North Pacific Gyre Oscillation (NPGO) pattern, the second-leading mode of North Pacific SST and sea surface height (SSH) variability, while the more "canonical" eastern Pacific events correlate more closely with the PDO (Newman et al., 2016).

A somewhat different perspective is offered by Wills et al. (2018). The framework used by them also indicates a strong linkage between fluctuations in the Aleutian low and North Pacific upper ocean response, but suggests that conditions in the tropical Pacific may not be as important to the Aleutian low on multi-year time scales as previously supposed. In general, the connections between the tropical and North Pacific were never really thought to be a solved problem, and both the research that is emerging, and unexpected manifestations of recent ENSO events, illustrate our incomplete understanding of this system.

Non-stationarity in the PDO and NPGO in the historical record

It is unclear whether principal component analysis (PCA) or other techniques relying on modes of variability that feature fixed spatial patterns are necessarily the best way to

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characterize the North Pacific climate system. There certainly seems to be evidence that the primary climate modes that have been identified wax and wane in their correspondences with biological variables. This was illustrated by Kilduff et al. (2015) with respect to Pacific salmon survival rates, which appear to be more strongly related to the PDO prior to the 1980s and to the NPGO in more recent times. Similar results were found by Litzow et al. (2018) who also showed that this change included a shift in the location of the SLP anomaly distributions associated with variability in the PDO. An additional regional example is represented by the western North Pacific subtropical high (WNPSH) in summer, whose co-variability with the atmospheric circulation for the North Pacific as a whole fluctuates on decadal time scales (Yun et al., 2015). There are good reasons why the PCA framework is often used, in that the formalism is well established, and the use of stationary patterns simplifies analysis to consideration of only temporal variations. On the other hand, it is unclear the extent to which these patterns are actually stationary, in that they are not necessarily fundamental from a dynamical perspective, and plausibly may evolve with the changing climate. In the 2009–2016 focal period there was considerable interannual variability associated with El Niño/La Niña, but the dominant signal, perhaps indicative of future climate change scenarios, was the appearance of the marine heatwave starting in 2014.

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Highlights

- In the 2009–2016 time period initial conditions of relatively cool ocean temperatures changed to predominately warm ocean temperatures, particularly in the eastern and northern regions of the North Pacific.
- During the fall and winter of 2013 there was much less cooling of the surface waters than normal, triggering a significant marine heatwave in the Northeast Pacific in 2014–2016.
- Over the past 25 years sea level has been rising throughout the North Pacific, and the rate of increase accelerated during the 2009–2016 focal period.
- In PICES region 17, reduced ice cover has been evident since 1984, and was consistently below normal between 2009 and 2016. Even during the coldest winter of 2011–2012, the ice cover did not reach its normal level with only about 80% of the region occupied by ice.

Chapter 3: The Physical Ocean

Authors: Peter C. Chandler and Vyacheslav B. Lobanov

Ocean circulation

The upper ocean circulation of the North Pacific consists of rotating gyre systems driven primarily by atmospheric forcing (Figure 3-1). Trade winds near the equator drive a westward flow before turning north to become the warm Kuroshio Current. This transport of warm tropical water to mid-latitudes vents large amounts of heat and moisture to the atmosphere affecting the atmospheric jet stream, mid-latitude storms, and ocean carbon uptake. Over the past 110 years, subtropical western boundary currents show warming rates two to three times faster than the global mean surface ocean warming rate (Wu et al., 2012). The northward flowing Kuroshio joins the cool southward Oyashio Current to form the eastward Kuroshio–Oyashio Extension (KOE) and North Pacific Current.

The prevailing clockwise rotation of the oceanic subtropical gyre results in a convergence zone at the southern edge of the North PacificTransition Zone, associated with the southern boundary of the westerlies, where buoyant organic and inorganic matter aggregate. The nutrient-rich subarctic Pacific exports water northward to the Arctic Ocean and southward to the subtropical Pacific, significantly increasing the productivity of these areas. The resulting Transition Zone Chlorophyll Front (TZCF; Figure 3-1) between the subtropical and subarctic oceans attracts many species of fish, marine mammals, and marine birds.

The cyclonic Alaska Gyre consists of the Alaska Current along the west coast of Canada, a wind driven nutrient-poor current with a freshwater core, and the Alaska Stream, a nutrient-rich, narrow, deep, high-speed current that flows southwestward along the Aleutian Islands. The currents of the Bering Sea form a cyclonic gyre, including the Aleutian North Slope Current, the Bering Sea Slope Current, and the Kamchatka Current. Currents in the northern Bering Sea advect nutrients, organic carbon, and plankton from the Pacific into the Arctic primarily driven by differing sea-level heights between the North Pacific and Arctic oceans (Aagaard et al., 2006,

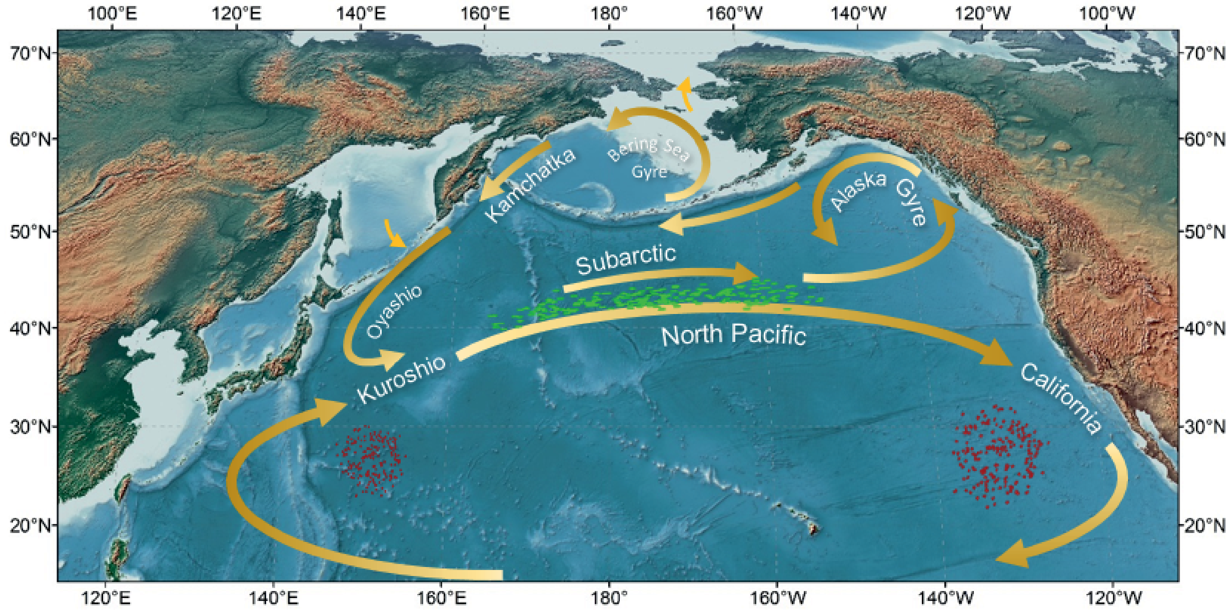

Figure 3-1. Schematic diagram of the prevailing surface currents in the North Pacific Ocean, showing the region associated with the Transition Zone Chlorophyll Front in green and the "garbage patches" in red.

Grebmeier et al., 2015). The southward flowing Kamchatka Current mixes with water flowing from the Okhotsk Sea (PICES region 17) forming the Oyashio water (Yasuda, 1997) that flows southwestward as the western boundary current of the subarctic gyre. This area, known as the Western Subarctic Gyre, is considered the most productive in the oceanic Pacific, with high abundances of zooplankton providing food for fishes, whales, and marine birds.

In 2013, winter winds, which are typically from the southwest in the transition zone, were blocked by southerly winds along the western edge of a high pressure ridge that had formed in the Northeast Pacific. This pattern continued for several months, reducing the zonal winds over the area 45–50°N, 140–150°W to an average of 1.6 m s^{-1}, well below the 1948–2012 average of 4.5 ± 1.3 m s^{-1}, and increasing the southerly component to 4.7 m s^{-1} from the average 2.9 ± 1.5 m s^{-1} (Whitney, 2015). Consequently, during the fall and winter of 2013 there was much less cooling of the surface waters than normal, triggering the significant 2014–2016 marine heatwave in the Northeast Pacific (see Breakout Box: Northeast Pacific marine heatwave, page 24) .

The North Pacific Subtropical High pressure cell is located in the eastern oceanic subtropical gyre centred near 130°W, 25°N. The anti-cyclonic circulation around this high pressure zone causes surface currents and floating debris to converge towards the centre. This gyre within a gyre between Hawaii and California has generated what is termed the "garbage patch" of the eastern Pacific (Howell et al., 2012). Monitoring and modelling efforts to quantify the size and density of the debris field indicate both are increasing with time.

Another debris field ("garbage patch") has been identified in the western Pacific south of Japan. The Kuroshio extension exhibits a semi-permanent recirculation gyre that weakens and strengthens due to fluctuations in the wind stress field (Qiu and Chen, 2005). A stronger recirculation gyre corresponds to a stronger flow in the Kuroshio extension, and an increase in sea surface height. Conversely, a more southerly and meandering flow in the Kuroshio extension is associated with a weaker recirculation gyre. It is expected that the greater the strength of the recirculation gyre, the greater the accumulation and retention effect on marine debris (Howell et al., 2012).

Sea level

Changes in global sea level have been determined using tide gauge records from coastal stations and satellite altimetry data. Mean sea level is rising primarily because global temperatures are rising, causing ocean water to expand and glaciers and land ice to melt. There has been an acceleration in the rise of sea level in recent decades as ocean waters warm and as the rates of ice loss from the Greenland and Antarctic ice sheets increase (IPCC, 2019).

Based on worldwide tide gauge records and more recent (since 1993) satellite measurements, it is widely accepted that global sea level has risen more than 20 cm since the late 19th century. This is equivalent to annual sea level rise rates of about 1 mm per year in the early part of the 20th century to more than 3 mm per year over the past decade or so.

Sea level variability at a regional scale can be influenced by both thermosteric changes and fluctuations in wind stress that change the ocean circulation (Köhl and Stammer, 2008). For example, high sea level along the Japanese coast in the 1950s is attributed to negative wind stress curl anomalies over the North Pacific associated with a negative phase of the Pacific Decadal Oscillation (PDO), whereas the rise in sea level observed since the 1990s is due primarily to heat and freshwater forcing (Sasaki et al., 2017). Along the west coast of North America climate patterns such as the El Niño–Southern Oscillation (ENSO) affect winds and ocean circulation, raising local sea level during warm phases (from 10 to 30 cm during the winter months of an El Niño) and lowering sea level during cool phases (e.g., La Niña) (National Research Council, 2012).

The sea level data shown in Figure 3-2 are derived from time series of daily gridded observations with a horizontal resolution of 0.25° x 0.25°, obtained by merging altimetry measurements from at least two satellites using TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3 as references. The altimetry data are combined using the DUACS processing system (Pujol et al., 2016), and provided by the Copernicus climate change service (C3S). Over the past 25 years sea level has been rising throughout the North Pacific, and the rate of increase accelerated during the 2009–2016 focal period.

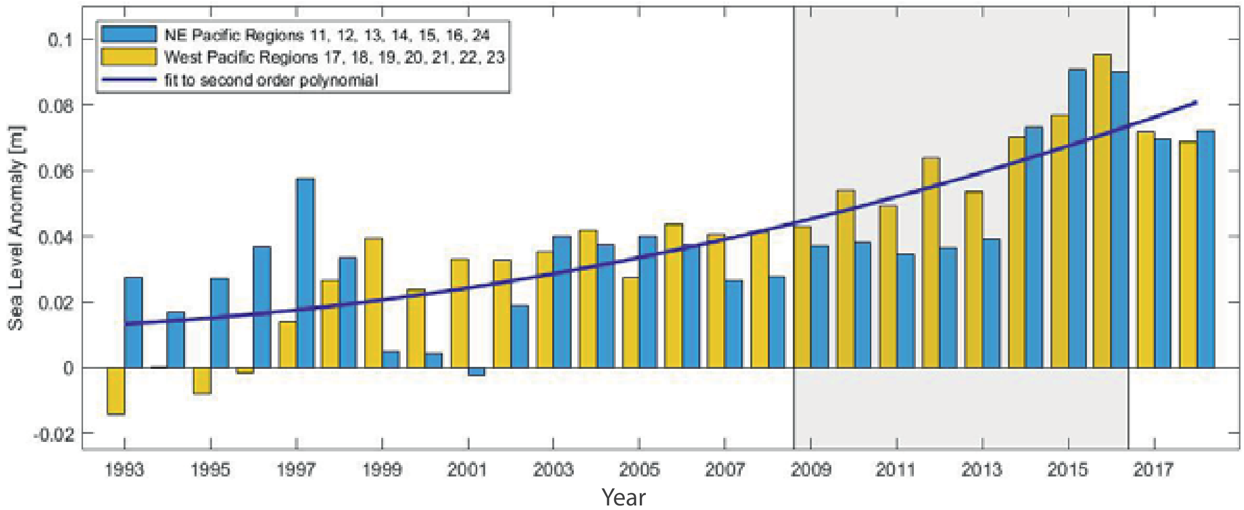

Figure 3-2. Annual sea level anomaly computed with respect to a 20-year mean reference period (1993–2012) combined for PICES regions in the western and Northeast Pacific from: https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global.

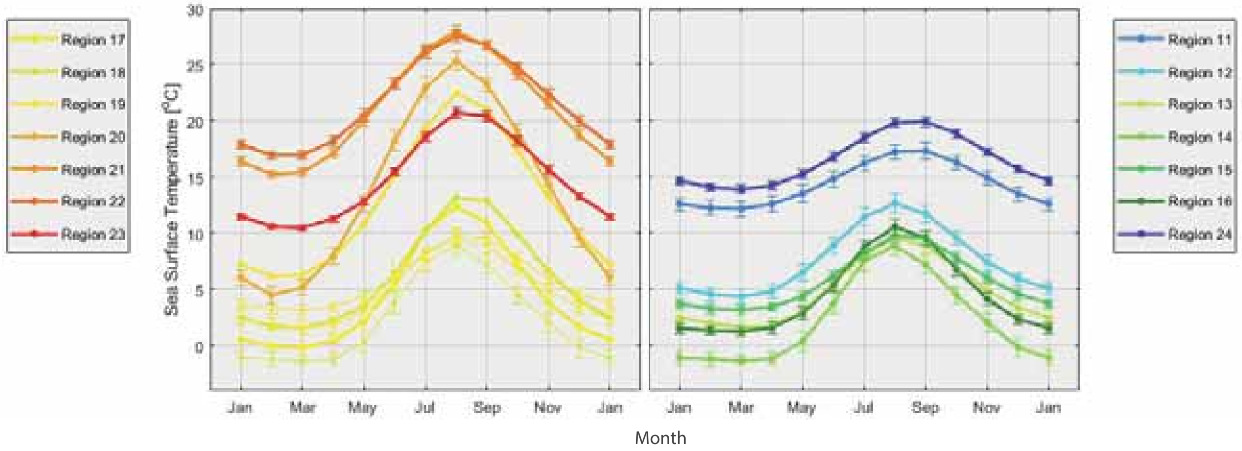

Figure 3-3. The average monthly sea surface temperature for each PICES region based on 30 years of NOAA Extended Reconstructed Sea Surface Temperature V4 (ERSST) data, 1989–2018. Error bars represent the standard deviation.

Ocean temperature and salinity

The temperature and salinity of water in the North Pacific Ocean changes by location, depth, and time. In general, the temperature of surface waters (sea surface temperature, SST) varies with air temperature while deeper waters are influenced more by currents. Additionally, there is interannual and interdecadal variability associated with atmospheric systems, notably the ENSO, and a trend of increased warming as air temperatures rise due to climate change.

The global ocean temperature dataset (ERSST) with a spatial resolution of 2° x 2° (Huang et al., 2015) was used to analyse the variability of the SST for the 14 PICES regions. As seen in Figure 3-3, the temperature changes with the seasons although there are clear differences in the annual range for each region. Further analysis of these data (Figure 3-4) shows how SST, using the annual anomalies from the 30 year average (1989–2018), has changed over time. It can be seen that in the 2009–2016 focal period initial conditions of relatively cool ocean temperatures changed to predominately warm ocean temperatures, particularly in the eastern and northern regions of the North Pacific. The regional changes in SST are also evident in the NOAA quarter-degree resolution Optimum Interpolation Sea Surface Temperature (OISST) dataset when conditions from 2009–2012 are compared to those from 2013–2016.

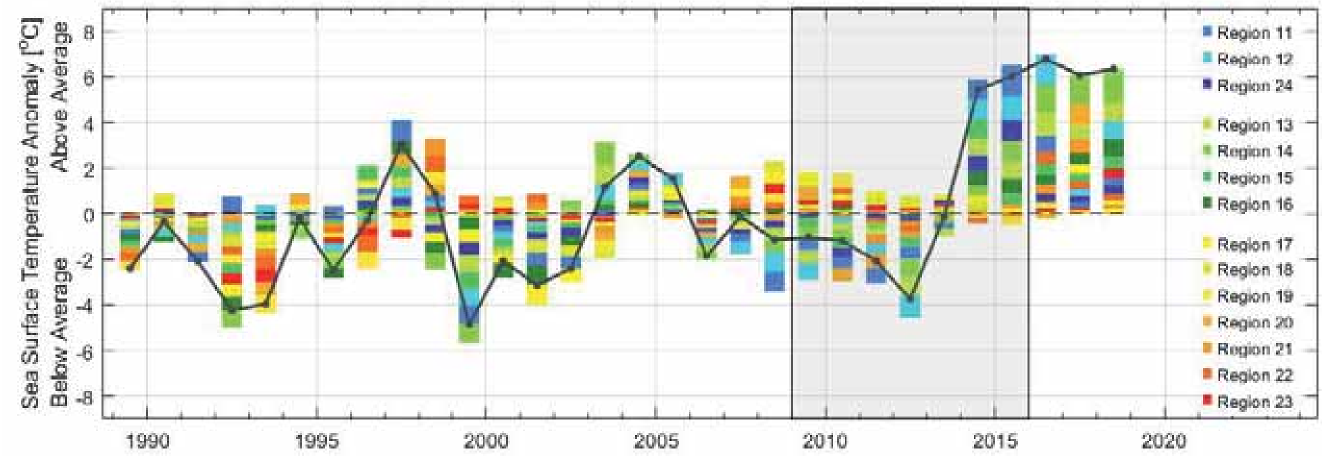

Figure 3-4. Annual sea surface temperature anomalies for each PICES region based on 30 years of NOAA ERSST data. For each year the anomalies are ordered from top to bottom by the magnitude of the anomaly. Black line represents the combined anomalies for all regions.

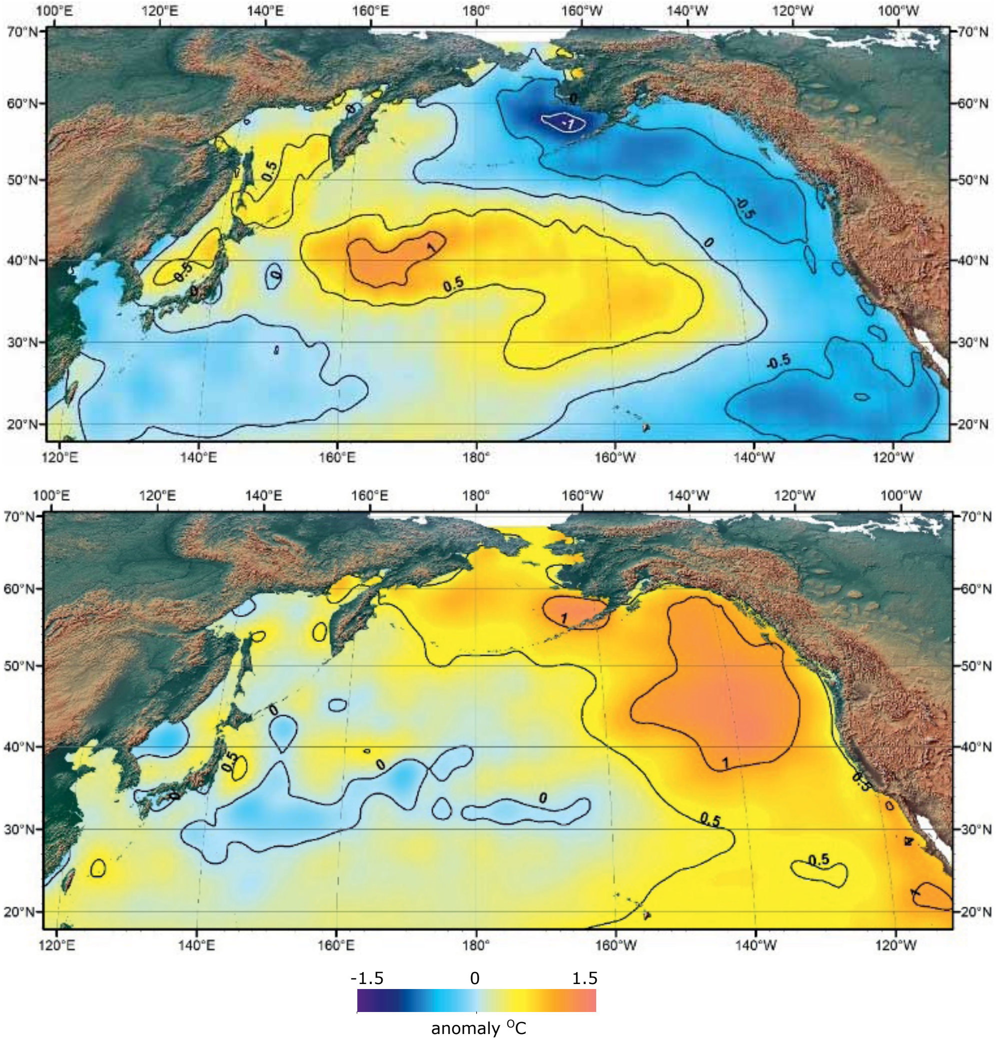

Figure 3-5. Sea surface temperature anomaly maps showing an SST pattern consistent with a negative Pacific Decadal Oscillation (PDO) phase in 2009–2012 (upper panel), and the change to a positive phase PDO pattern in 2013–2016 (lower panel).

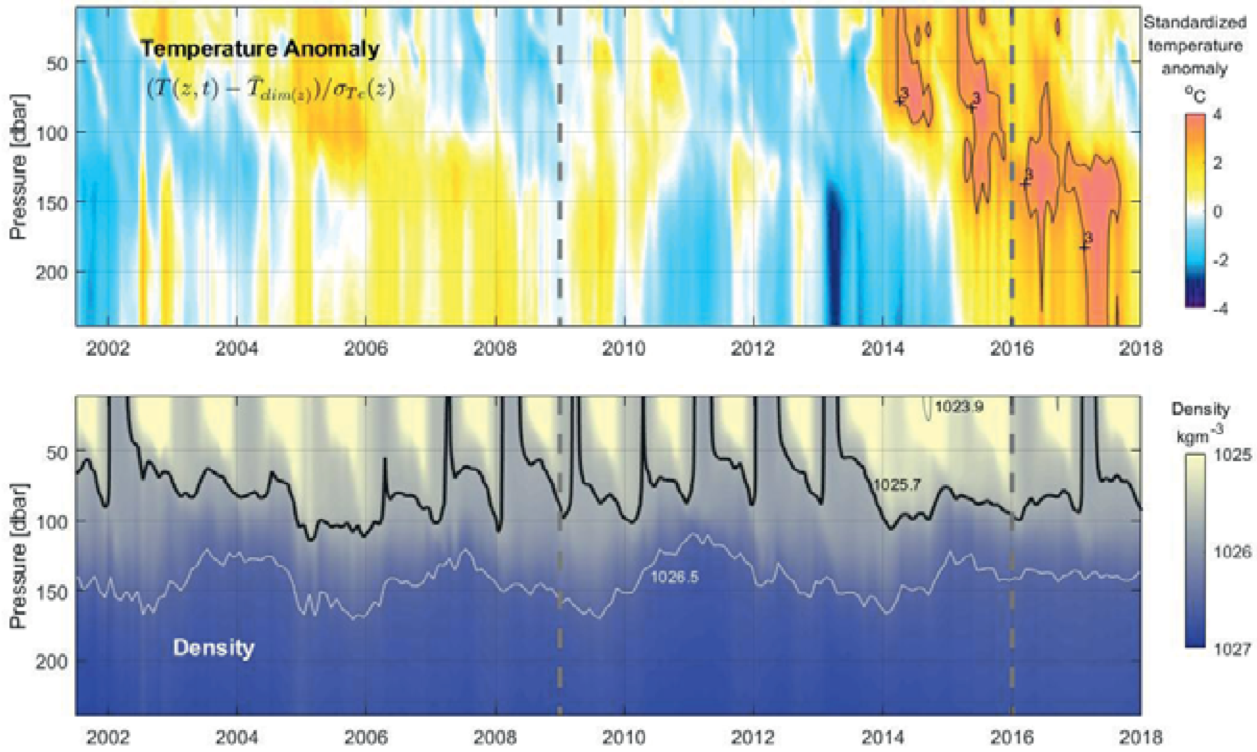

Figure 3-6. Upper panel: Temperature anomalies of Argo data observed near Station Papa relative to the 1956–2012 seasonally corrected data from Station Papa. Dashed lines show regions with anomalies 3 standard deviations above the mean. Lower panel: Density observed by Argo floats near Station Papa. Thick black line shows the 1025.7 kg m^{-3} isopycnal. Vertical dashed lines indicate the periods spanning 2009–2016.These data were collected and made freely available by the International Argo Program and the national programs that contribute to it (http://argo.jcommops.org). The Argo Program is part of the Global Ocean Observing System.

Figure 3-5 shows the SSTs as anomalies from the 1981–2010 climatology, with a cool eastern ocean in the first half of the 2009–2016 period and a pattern representative of the PDO in a negative phase. During the following three years (2013–2016) the Northeast Pacific was anomalously warm, typical of the positive phase of the PDO. Changes in the PDO index reflect the first mode of SST variability in the North Pacific Ocean, which is associated with other changes in the physical environment and the productivity of marine ecosystems.

Since 2001 the data available from the Argo array of free-drifting profile floats in the ocean has provided a near continuous time series of temperature and salinity to a depth of 2000 m. At the position of the long-term ocean monitoring station Papa (50°N, 145°W), profile information from the surrounding Argo floats has been interpolated to show normalized temperature anomalies versus time and depth (Figure 3-6, upper panel). These anomalies are relative to mean conditions from 1956–2012, and are standardized by the seasonally and depth varying standard deviation computed over the same period. The 2009–2016 period of interest is characterized by generally cooler than normal ocean temperatures near the surface until late 2013 when distinctly warmer than normal conditions prevailed until 2017. While subsurface temperatures remained above normal from 2004 until 2010, there followed a period of lower than normal temperatures until a marine heatwave emerged in 2014. During the marine heatwave of 2014 to 2016, ocean temperature anomalies exceeded three standard deviations from the mean. As the temperatures of the surface waters reverted to more normal conditions in 2017, positive subsurface anomalies continued to be observed.

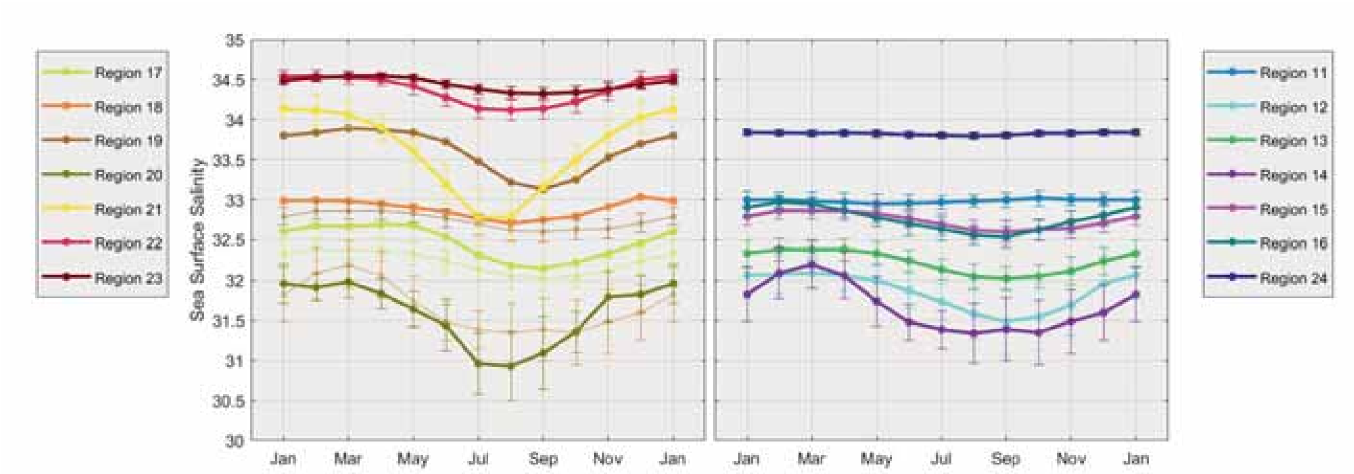

Figure 3-7. Average monthly sea surface salinity for each PICES region based on 25 years of Met Office Hadley Centre data, 1993–2018. Error bars represent the standard deviation.

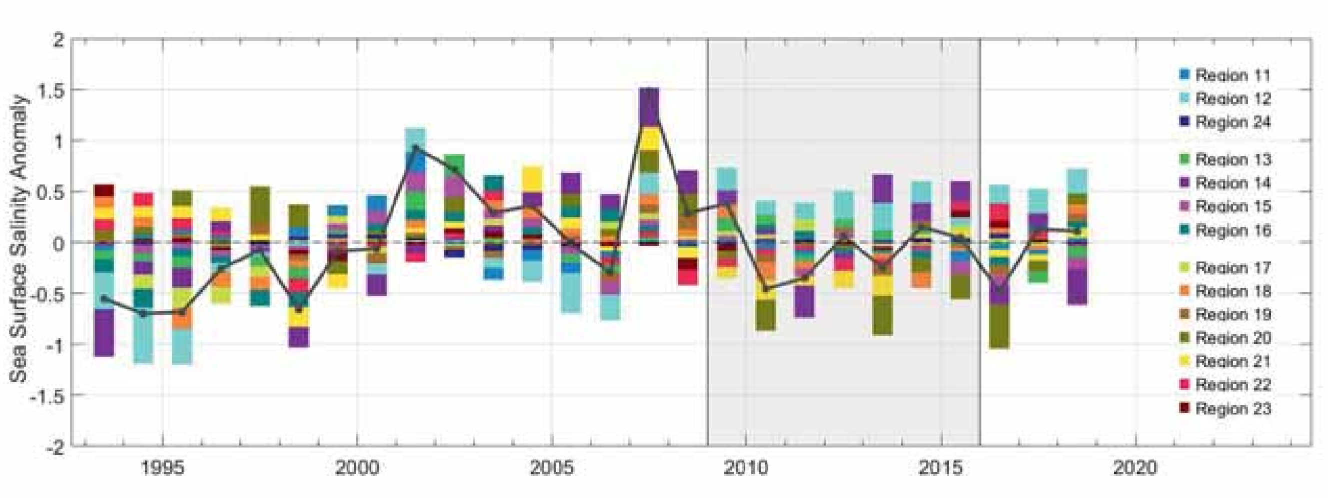

Figure 3-8. Annual sea surface salinity anomalies for each PICES region based on 25 years of Met Office Hadley Centre data. For each year the anomalies are ordered from top to bottom by the magnitude of the anomaly. Black line represents the combined anomalies for all regions.

The corresponding time series of Argo density data is shown in the lower panel of Figure 3-6. The annual winter mixing of the upper ocean, as indicated by the depth of the 1025.7 kg m^{-3} contour reaching the surface, occurred regularly from 2007 until 2013, and resumed in 2017. Between 2013 and 2017 the upper 100 m of the ocean at Station Papa experienced increased stratification as warmer temperatures and less mixing kept the density of surface waters relatively low.

Figures 3-7 and 3-8 show the regional variability of sea surface salinity, in a similar format used for SST in Figures 3-3 and 3-4. The source of the salinity data is the EN4 dataset from the Joint DECC/Defra Met Office Hadley Centre (Good et al., 2013).


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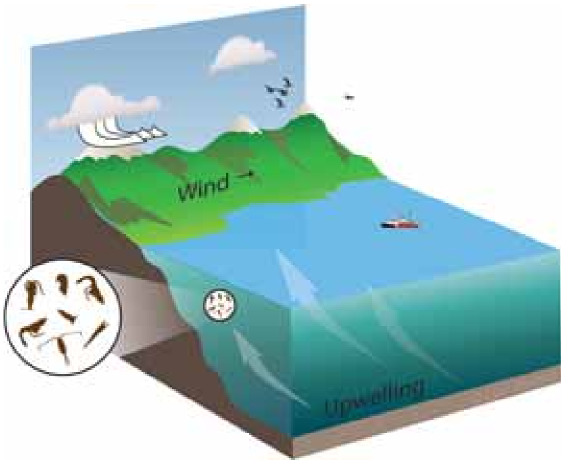

Upwelling

Along oceanic eastern boundaries, such as PICES region 11, equatorward wind stress (winds from the northwest that typically predominate from April to October) and the Earth's rotation combine to force surface waters offshore and the vertical transport of deeper nutrient-rich cold waters into the sunlit euphotic zone of the coastal ocean. Upwelling is an important driver of primary production and in general an earlier, longer, and more intense upwelling season relates to greater primary productivity; indices such as the "Bakun Index" are used to monitor this intensity (Schwing et al., 1996). Figure 3-9 shows the interannual variability of the upwelling as the anomaly of the Bakun Index compared to a (1981–2010) climatological period. During the 2009–2016 focal period, it can be seen that lower than normal upwelling in the first two years was followed by coast-wide above average upwelling, particularly in the mid-latitudes.

Upwelling on the western side of the Pacific Ocean (PICES regions 20 and 21) typically starts in June, develops to its strongest condition in July and August, and then weakens and eventually vanishes in late September (Lou et al., 2011). The process is driven primarily by alongshore winds, and enhanced by local bathymetry. Upwelling off the northeastern part of Chinese Taipei, associated with a cold cyclonic eddy, is regarded as an important conduit for water exchange with the Kuroshio (Wong et al., 2000). The cold eddy is characterized by low temperature, high salinity, high density, low dissolved oxygen, high phosphate, high silicate, and high nitrate (Tseng et al., 2012) and is influenced by the dynamic balance between the meandering Kuroshio Current and coastal water from the south flowing onto the continental shelf.

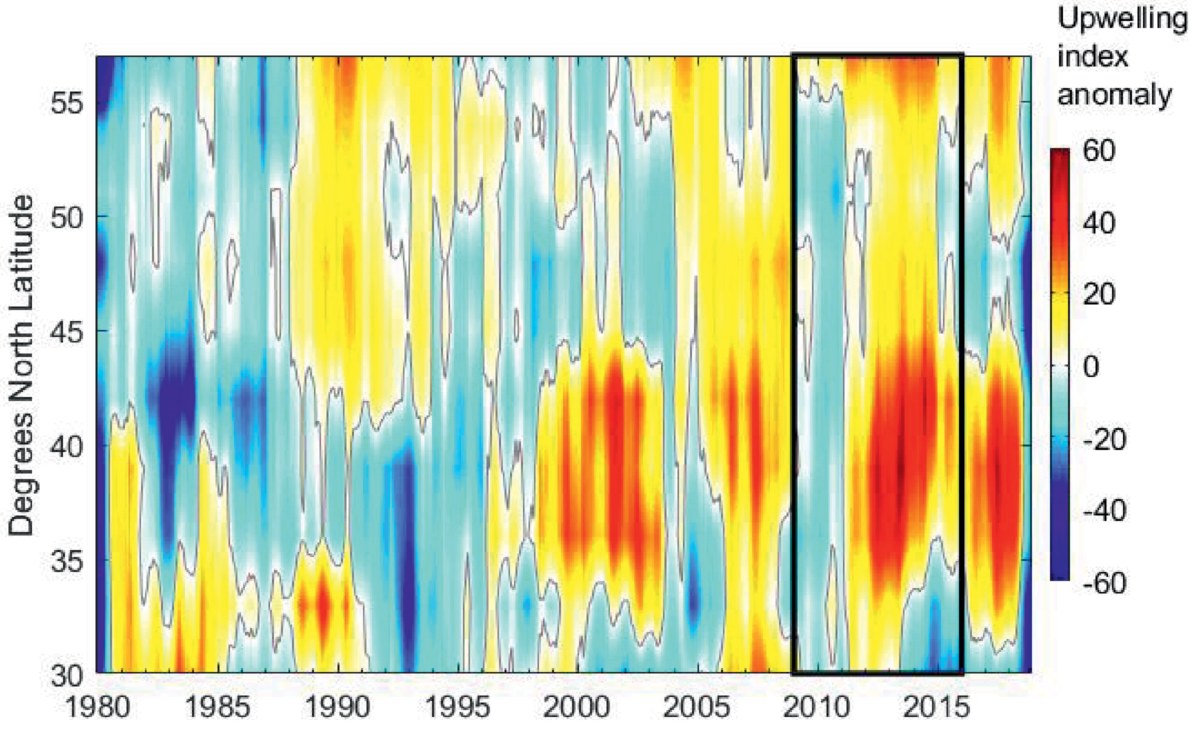

Figure 3-9. Monthly mean anomalies (based on the 1981–2010 climatology) of the Bakun Index calculated using the 3° Fleet Numerical Meteorology and Oceanography Center sea level pressure grid and smoothed using a 12-month running mean. Framed area is the focal period of this report. Source: Environmental Research Division, NOAA Fisheries, Southwest Fisheries Science Center.

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Sea ice

The high-latitude regions of the North Pacific are clearly responsive to the effects of global warming, and changes in the northern Bering Sea have been particularly striking. In the past historical record this region regularly experienced over 5–6 months of sea ice each year, even when the North Pacific Ocean in an overall sense was experiencing warm conditions. Recently this has no longer been the case, with three out of the four winters from 2015 through 2018 featuring greatly reduced ice cover (Stabeno et al., 2018), continuing into 2019. An important factor appears to be conditions in the Chukchi Sea north of the Bering Sea, where sea ice is tending to develop later in the fall. Postponement in the development of sea ice in the Chukchi Sea results in the late arrival of sea ice in the Bering Sea. Unless there is persistently cold weather, the consequence is less ice for the Bering Sea for the winter season. The implication for the marine ecosystem includes changes in lower-trophic community structure, notably a reduction in ice algae, and a tendency for greater pelagic productivity at the expense of the benthos. The overall warming observed for the Bering Sea, in turn, has served to the warm the Chukchi Sea, the latter of which is subject to the northward flow of warmer water through the Bering Strait in the summer, as well as central Arctic influences.

Sea ice that forms in the Arctic proceeds southward where its maximum extent in March or April is determined by a combination of processes, including transport by currents, air–sea heat flux, and melting at the leading edge of the ice (Sigler et al., 2011). Sea ice begins to retreat in late winter or early spring and is absent by late June; its extent and duration are important influencers of ice algae and primary production.

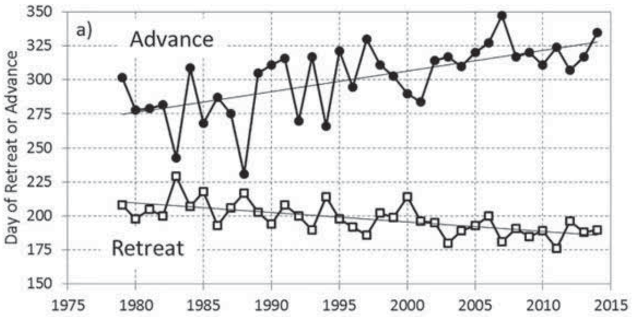

Figure 3-10. Time series and linear trends of sea ice retreat and advance along the northern boundary of the Bering Sea. Adapted from Serreze et al. (2016).

Based on the analysis of Serreze et al. (2016), the beginning of the open water period at the northern boundary of the Bering Sea (the retreat date) is defined as the first day of the year when the average sea ice concentration in an area to the north of the boundary is less than 30%. The end of the open water period (the advance date) is the first day after the seasonal ice extent minimum when the average sea ice concentration in this sector exceeds 30%. Figure 3-10 shows the time series of sea ice retreat and advance, indicating more days of open water (2.22 days per year) due more to the trend toward a later advance day than an earlier retreat day.

Figure 3-11 shows the interannual variability (attributed to changes in regional atmospheric conditions, SST, and salinity) of the mean sea ice cover in the Bering Sea and the Tartar Strait, with no clear long-term trend. In PICES region 17 (Okhotsk Sea) the baseline ice cover from

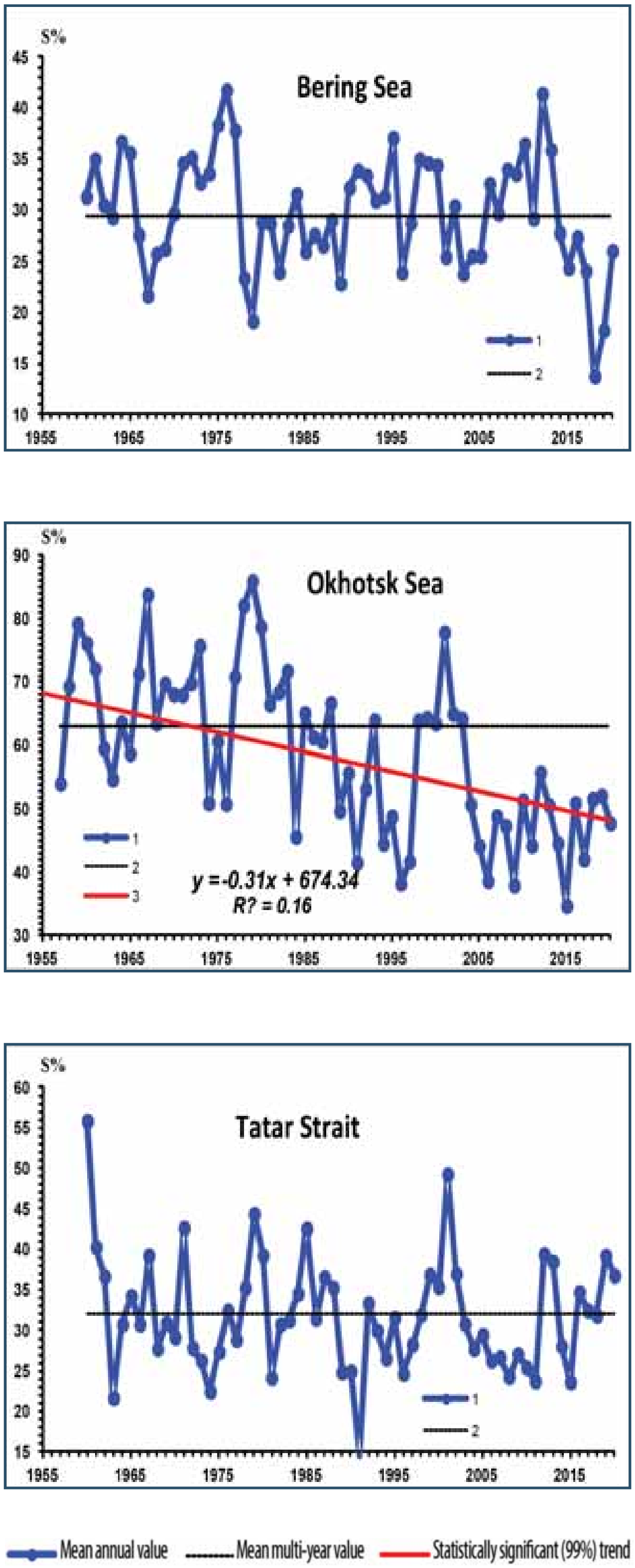

Figure 3-11. Mean winter sea ice cover in PICES regions 16 (Bering Sea), 17 (Okhotsk Sea) and 19 (Tatar Strait). S% is a percent of the ice covered area to the whole area of the sea. Updated by the authors from Ustinova and Sorokin (2013).

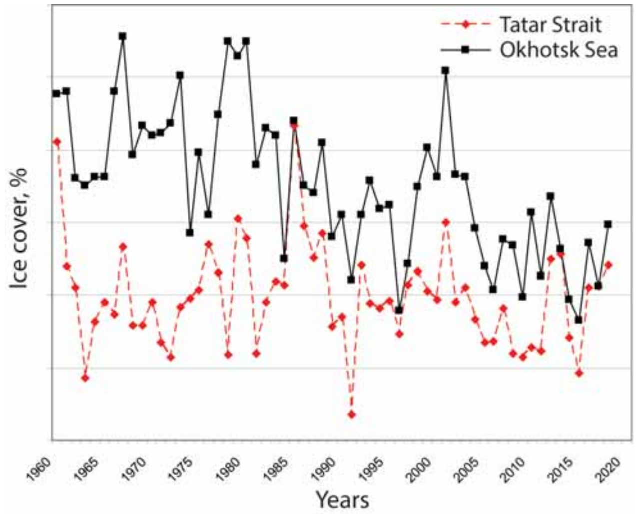

Figure 3-12. Ice cover variations in the Tatar Strait and the Okhotsk Sea, 1960–2018. Adapted from Pishchalnik et al. (2019).

January to May is based on observations since 1960. Reduced sea ice cover has been evident since 1984, and has been consistently below normal between 2009 and 2016. Even during the coldest winter of 2011–2012, the sea ice cover did not reach its normal level, with only about 80% of the region occupied by ice (Figure 3-12).

Ice conditions in the West Kamchatka area impact the winter fishery in the Okhotsk Sea (PICES region 17). The low ice cover in this area over the 2009–2016 focal period provided greater access to the fishing grounds and placed more pressure on the fishery. The winters of 2011, 2013, and 2014 were distinguished by an early end of the heavy ice period – in late March.

Quasi-stationary polynyas along the northern and northwestern shores of the Okhotsk Sea caused by winter monsoon winds are important for herring spawning – these ice-free water belts are necessary for earlier and successful spawning. Because of weak winter monsoons from 2009 to 2015, the polynyas were either late in forming or were absent (2012). However, after forming late they were relatively large and stable in 2010, 2014, and 2015 and these years were relatively favourable for herring spawning.

Kirill Kivva

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Breakout Box

Northeast Pacific marine heatwave 2014–2016

Author: Peter C. Chandler

Marine heatwaves are events characterized by extremely warm temperatures over an area of the ocean for an extended period of time compared to expected conditions. They have been observed in all oceans of the world and can have significant impacts on marine ecosystems.

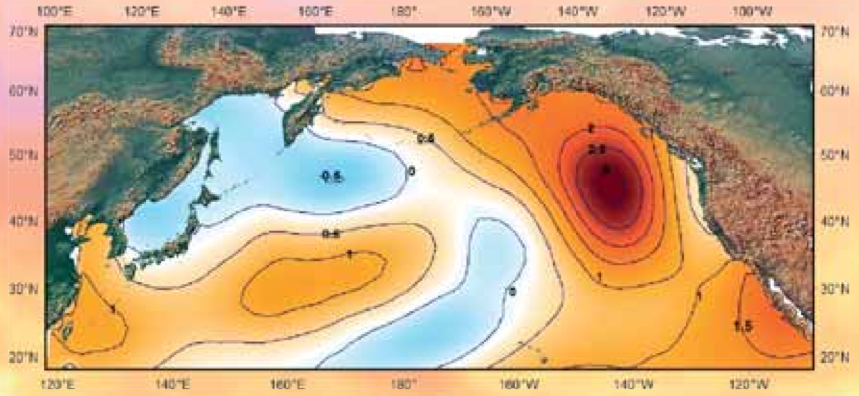
In the late fall of 2013, a persistent ridge of atmospheric high pressure in the Northeast Pacific deflected the typically strong winter storms northwards, and without the mixing generated by these storms the surface waters, retained their summer heating. The result was much warmer than normal sea surface temperatures by late winter over a large region, and during the spring and summer of 2014 these warm sea surface temperature anomalies had expanded to coastal waters (PICES regions 11 and 12) and were given the nickname "the Blob" (Bond et al., 2015).

This event was accompanied by a transition in the Pacific Decadal Oscillation (PDO) from negative to positive in the spring of 2014, with a mostly positive phase for the PDO persisting into 2019. In 2014, the upper-ocean heat content in the tropical Pacific also increased and models predicted a major El Niño for the winter of 2014–2015. However, while the very strong El Niño did not occur until the summer of 2015, warmer than normal conditions continued throughout 2014 and 2015. As shown in the figure below, sea surface water temperatures for a large area off the west coast of North America in the summer of 2015 were over 3°C above normal. It was the storms and mixing associated with La Niña at the end of 2016 that cooled the ocean and signaled the end of the Blob.

A categorization scheme proposed by Hobday et al. (2018) classifies marine heatwaves into four categories of increasing severity (moderate, strong, severe, extreme). The 2014–2016 marine heatwave in the Northeast Pacific was classified as severe for 13% of the 711-day duration.

The anomalously warm ocean conditions resulted in changes to the marine ecosystem – some immediate and others long-lasting. These changes included extremely low chlorophyll levels during the late winter/spring of 2014 in the region of the warm anomalies, likely due to suppressed nutrient transport into the mixed layer (Whitney, 2015). A sustained harmful *Pseudo-nitzschia* spp. bloom occurred along most of the coastline of PICES region 11, producing an outbreak of the neurotoxin – domoic acid, (McCabe et al., 2016), negatively impacting the clam and crab populations as well as the sardine and anchovy commercial and recreational harvest. The abundance of energy-rich sub-Arctic and boreal zooplankton diminished as southern warm-water species became predominant. Widespread mortalities of sea lions and Cassin's Auklets were documented, as were sightings of typically warm-water species in northern waters (Cavole et al., 2016).

Marine heatwaves in the North Pacific Ocean are expected to increase in intensity, relative to historical norms, as climate change continues to raise the heat content of the ocean. It is an open question whether climate change may influence atmospheric circulation patterns and thereby impact the frequency and spatial characteristics of these events.



June 2015 sea surface temperature anomaly (°C). Blue areas represent temperatures that are colder, and red areas that are warmer than the 1981–2010 average. Data source: NOAA_ERSST_V4, provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, on their website.

Winners

Toxic phytoplankton
Massive bloom closed important fisheries

Tropical, subtropical copepods
Northward range expansion with warm water

Market squid 2014-15
Increased fishery in north caused by range expansion

Rockfish
Increased recruitment in California

Tuna
Increased abundances along coast with increased sport fishing

Orcas
Increased birth rate caused by increased salmon abundances in some regions through population movements

Losers

Subarctic copepods, krill
Lack of food reduced population, distribution moved northward.

Market squid 2015-16
Reduced in south as distribution moved far north

Dungeness crab and mussels
Fishery closed due to toxicity

Salmon
Warm temperatures decreased recruitment for some species

Groundfish
Potential loss of habitat due to hypoxia

Marine birds, seals and sea lions
Massive die-offs due to lack of food

Baleen whales
Expected to decline due to lack of food

Organisms observed to be positively and negatively impacted by the marine heatwave. Positively affected organisms are labeled as "Winners," while negatively affected organisms are labeled as "Losers." Organisms are presented from lower to higher trophic levels. Adapted from Cavole et al. (2016).

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McCabe, R.M., Hickey, B.M., Kudela, R.M., Lefebvre, K.A., Adams, N.G., Bill, B.D., Gulland, F.M.D., Thomson, R.E., Cochlan, W.P., Trainer, V.L. 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. Geophysical Research Letters 43: 10,366–10,376, doi:10.1002/2016GL070023.

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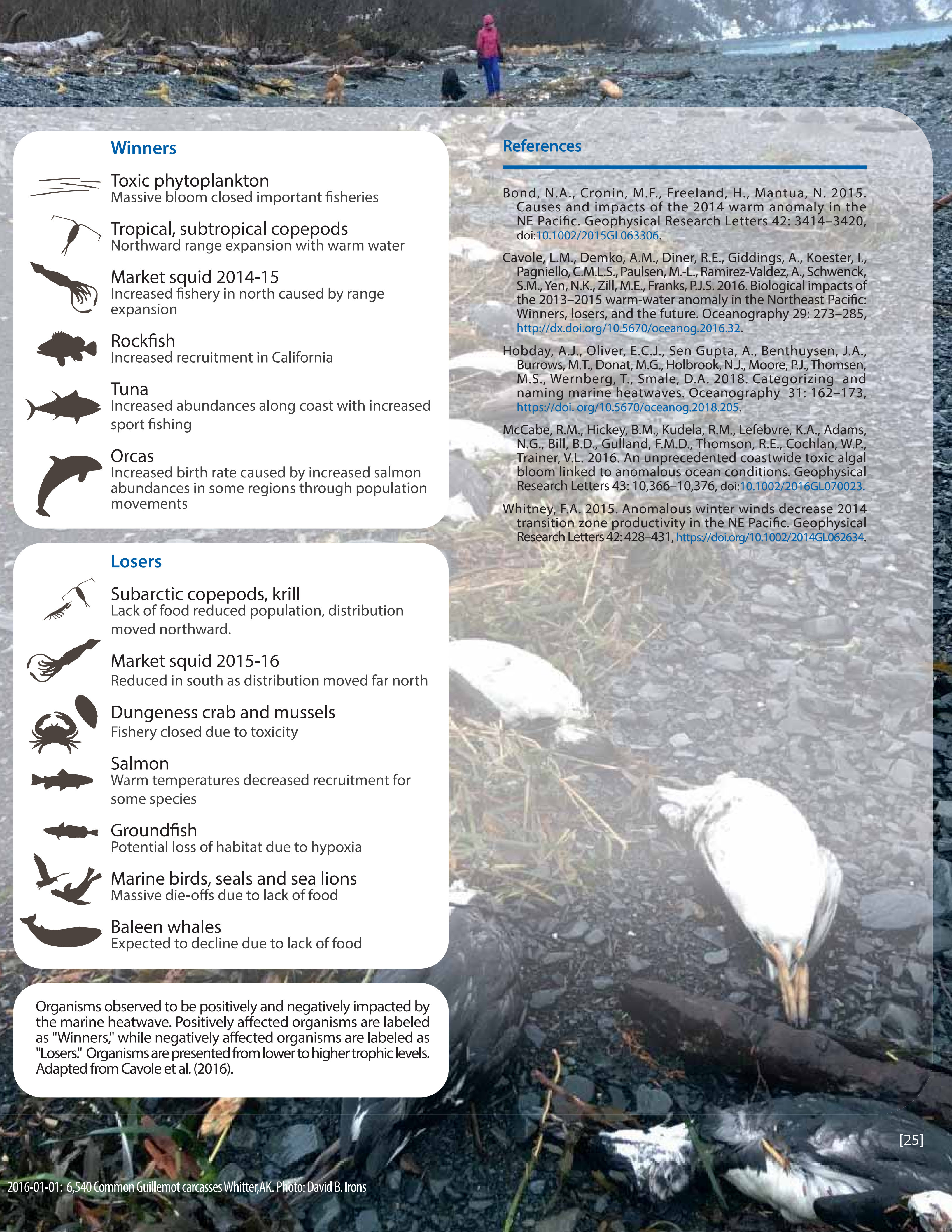
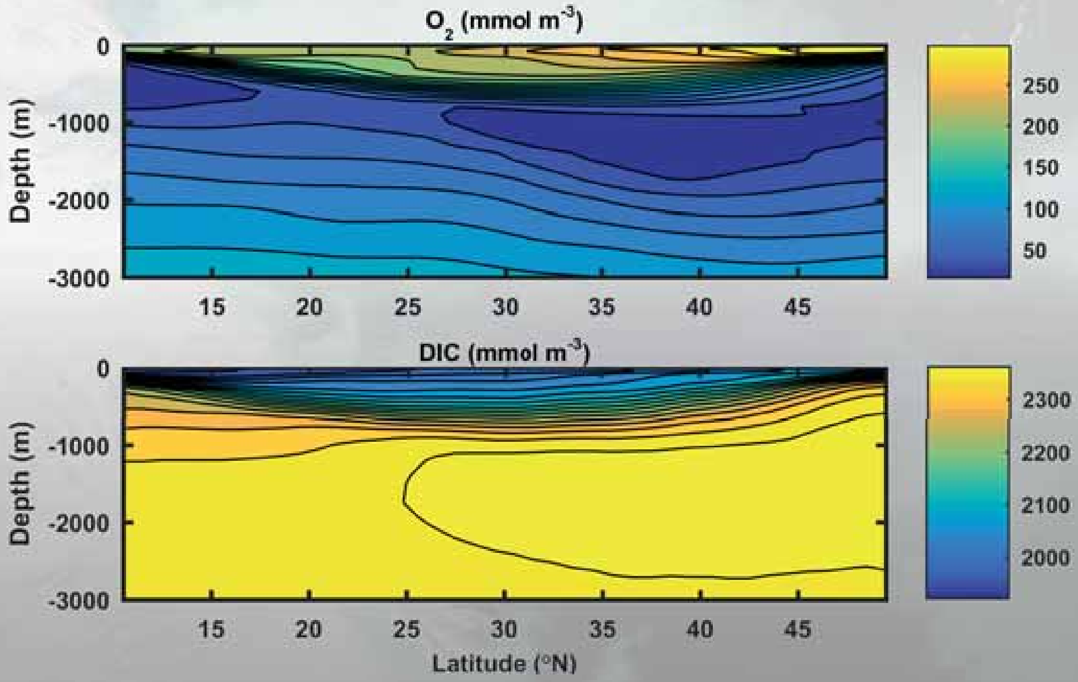


2016-01-01: 6,540 Common Guillemot carcasses Whitter,AK. Photo: David B. Irons

[4]

Highlights

- **Essential nutrients show significant temporal variation at both interannual and interdecadal time scales.**
- **Both ocean acidification and deoxygenation are increasing in almost all areas of the North Pacific and its marginal seas.**

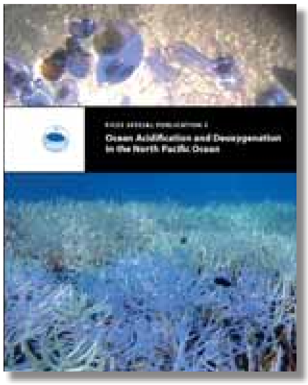


Distribution of dissolved oxygen (DO) and total dissolved inorganic carbon (DIC) along 160°W. Data from GLODAP2 and World Ocean Atlas 2014 courtesy of National Centers for Environmental Information (US). From Christian and Ono (2019).

Chapter 4: The Chemical Ocean

Authors: Tsuneo Ono and Kirill Kivva

Introduction



This chapter provides an overview of long-term changes in the marine chemistry of the North Pacific, specifically variability in oxygen content, essential nutrient levels, and ocean acidification. Further information is available in the PICES regional reports[1] and the recent and comprehensive review in PICES Special Publication 5, Ocean Acidification and Deoxygenation in the North Pacific Ocean (Christian and Ono, 2019)[2].

As described in the second North Pacific Ecosystem Status Report (McKinnell et al., 2010), global warming is associated with an increasing stratification of the upper ocean that diminishes vertical ventilation and results in a long-term trend of decreasing dissolved oxygen (DO; deoxygenation) and pH (ocean acidification). During the 2009–2016 focal period, an overall decline in DO and pH continued throughout the North Pacific Ocean as a linear trend with variability at natural decadal time scales in ocean climate (e.g., Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO)). In coastal regions, changes in anthropogenic loading of nutrients and organic substances provided an additional cause of deoxygenation and ocean acidification (OA).

Deoxygenation

A synthesis of deoxygenation trends derived from NPESR3 regional reports is given in Table 4-1 and shows subsurface deoxygenation in many regions of the North Pacific. Ocean deoxygenation has been detected in all regions of the North Pacific with some exceptions; the Alaskan coastal region and the Bering Sea (PICES regions 12, 13 and 16, respectively). Regions where deoxygenation has not been identified is likely due to a lack of data and indicates a need for more monitoring.

The increase in sea surface temperatures, attributable to global warming, leads to an increased stratification of the upper waters of the ocean and a reduced ventilation of oxygen from the surface to the deep ocean (Shmitko et al., 2017). The stratification also reduces the upward transport of nutrient-rich subsurface water and a corresponding trend towards lower oxygen and higher nutrients in waters below the surface layer (the pycnocline) (Whitney et al., 2013).

The relationship between deceasing oxygen and increasing nutrients has been observed throughout the North Pacific but as time series become longer, what was initially considered a linear trend may now be interpreted as inter-decadal variations overlapped with a long-term trend (Stramma et al., 2019). In general, the surface nutrient concentrations in the open North Pacific show variations corresponding to the PDO and NPGO (Di Lorenzo et al., 2008; Yasunaka et al., 2016). In PICES regions 18 and 23 (Oyashio and the western Subarctic), oxygen concentrations in subsurface waters showed variability corresponding to the PDO and the 18.6 year nodal tidal cycle. In these two regions the oxygen concentration of intermediate waters increased in the late 1970s, early 1990s and late 2000s. In PICES region 19, episodic increases in deep-water oxygen concentrations were observed in the early 1970s, late 1980s and early 2000s. While the interval of deep-ventilation events (i.e., oxygen increase) is similar between PICES region 19 and those observed in regions 18 and 23, the timing of increase in PICES region 19 precedes that of the other two regions by roughly 5 years. This may be an example of coastal modulation of large-scale climate variation.

An increase in DO in layers just below the seasonal pycnocline (50–300 m depth) has been observed recently in several regions including

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[1] https://meetings.pices.int/publications/special-publications/NPESR/2021

[2] https://meetings.pices.int/publications/special-publications/Special-Report%205-Ocean_Acidification.pdf

PICES regions 11, 17, 18, 20 and 23. This may be due to more intense mixing or lateral advection of more oxidized water as a consequence of local circulation changes. In 2012 the western Bering Sea and Oyashio regions experienced a short-term increase in oxygen and nutrients near the seasonal pycnocline as well as nutrients in the surface layer due to extreme winter cooling and convection along the eastern coast of Asia. Since 2009 increasing DO levels have been observed in the deep waters off the coast of British Columbia (Chandler et al., 2018). In other regions, episodic deep ventilation events are evident in the oxygen record, but more data are required to explain their causes and effects.

Eutrophication

In coastal waters, large-scale climate patterns are not always the leading modes of nutrient variability. For example, nutrient concentrations in PICES region 20 show a variability corresponding to precipitation independent of changes in the PDO or NPGO.

Changes in land use, production and utilization of fertilizers, discharge of waste and fossil fuel combustion mobilize nitrogen and phosphate into coastal environments (e.g., Nixon, 1995; Cloern, 2001) primarily via river discharge. However, atmospheric or underground water deposition may also contribute to this process of coastal eutrophication (e.g., Paerl, 1997). Eutrophication results in greater primary production which, in turn, often leads to bottom hypoxia. It also shifts the equilibrium in ecosystems not only due to change of overall nutrient cycles, but also to changes of ratios between inorganic nutrients (e.g., Justić et al., 1995) which can dramatically change community structures. These changes directly and indirectly affect protected species and commercial fish stocks and may lead to harmful algal blooms.

Eutrophication is most prominent in PICES regions 20 and 21 where significant nutrient loads are introduced to coastal waters by large rivers and wind, and is well documented for the Changjiang (Yangtze River) estuary (Jiang et al., 2014). Evidence of eutrophication includes significant temporal increases in nutrient levels and primary production and bottom hypoxia, as well as multi-year occurrences of algal blooms and green tides (macro-algae blooms) (Xing et al., 2015).

Coastal eutrophication in some other regions of the North Pacific may become as prominent as observed in PICES regions 20 and 21. For instance, there is evidence of riverine nutrient discharge increase and bottom hypoxia in the Salish Sea area (coastal British Columbia, PICES region 11; Khangaonkar et al., 2018, 2019).

Ocean acidification

As seen in Table 4-1, many of the PICES regions have too few pH data time series to examine trends. In those regions where data are available, OA has been detected both in surface waters and subsurface waters. There is also variability within regions, for example, Table 4-1 shows a general increasing trend for PICES region 11 from 2000–2018 but negative subsurface trends have been observed in other PICES areas. All subsurface OA trends are associated with deoxygenation trends, confirming that OA trends are not caused only by a temporal increase in atmospheric CO_2 but also result from reduction of water ventilation (e.g., Rios et al., 2015). This combined stress of both OA and deoxygenation is expected to cause severe impacts on marine organisms (Pörtner and Farrell, 2008).

Table 4-1. Long-term variation trends for nutrients, oxygen, and pH for each PICES region.

PICES region	Long-term variation trends			
	nutrient/ surface	nutrient/ subsurface	oxygen/ subsurface	pH/ subsurface
11				
12				
13	−			
14				
15	+			
16				
17			−	
18	+	−	−	−
19			−	−
20		+	−	
21				
22				
23	−	+	−	−
24			−	

Green plus signs (+) and red minus signs (−) represent positive or negative trends, respectively.

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Breakout Box

Eutrophication in the Yellow Sea

Author: Sinjae Yoo

The anthropogenic nutrient enrichment of the Yellow Sea started in the early 1980s with rapid industrialization in the region, and the increase in agricultural and industrial waste discharge. There are three major anthropogenic sources of inorganic nitrogen in the Yellow Sea: atmospheric deposition (Chen et al., 2010; Kim et al., 2011), river discharge (Yuan et al., 2008; Zhou et al., 2010; Li et al., 2015), and submarine ground discharge (Tan et al., 2018; Wang et al., 2018). Long-term time series of nutrients and chlorophyll-a have shown that the loading of inorganic nitrogen from these three sources has been increasing for several decades.

The nutrient levels, especially in the Changjiang River, have substantially increased over the last five decades (Liu et al., 2018). The observations from the Datong gauging station from 1960 to 2010 show that total nitrogen (N) and phosphorus (P) continuously increased while the volume of discharge remained at a relatively stable level (Liu et al., 2018). The increase in total nitrogen is largely attributed to increases in agricultural and industrial runoff, sewage wastewater, aquaculture, etc. (Müller et al., 2008; Liu et al., 2018). Over the past few decades there has been a 10-fold increase in the nitrate concentration in the Yellow Sea. From 1999 to 2009 annual primary productivity increased by 25% (Yoo et al., 2019), and the dissolved oxygen concentration and pH decreased. The saturation state of aragonite, Ω_{arag}, frequently approaches unity in many areas. Since 2008 there have been frequent large-scale green algal blooms observed in Chinese waters with a concurrent change in the nutrient ratio; the impacts on a basin-scale have not been fully assessed yet. Because the nutrient load from the major sources that drive eutrophication in the Yellow Sea continue to increase, the eutrophication there is very likely to intensify in the future. To accurately predict the future trend of eutrophication of the Yellow Sea, we need to better understand the contribution of each source and how ocean warming, eutrophication, and acidification interact.

Green tide on Qingdao beach, China. Xuanzheng Yuan, Qianguo Xing.


Eric Vance, USEPA


South China Morning Post, https://www.scmp


Jennifer Graham, USGS

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Wang, X., Baskaran, M., Su, K., Du, J. 2018. The important role of submarine groundwater discharge (SGD) to derive nutrient fluxes into River dominated Ocean Margins- the East China Sea. Marine Chemistry 204: 121–132, doi:10.1016/J.MARCHEM.2018.05.010.

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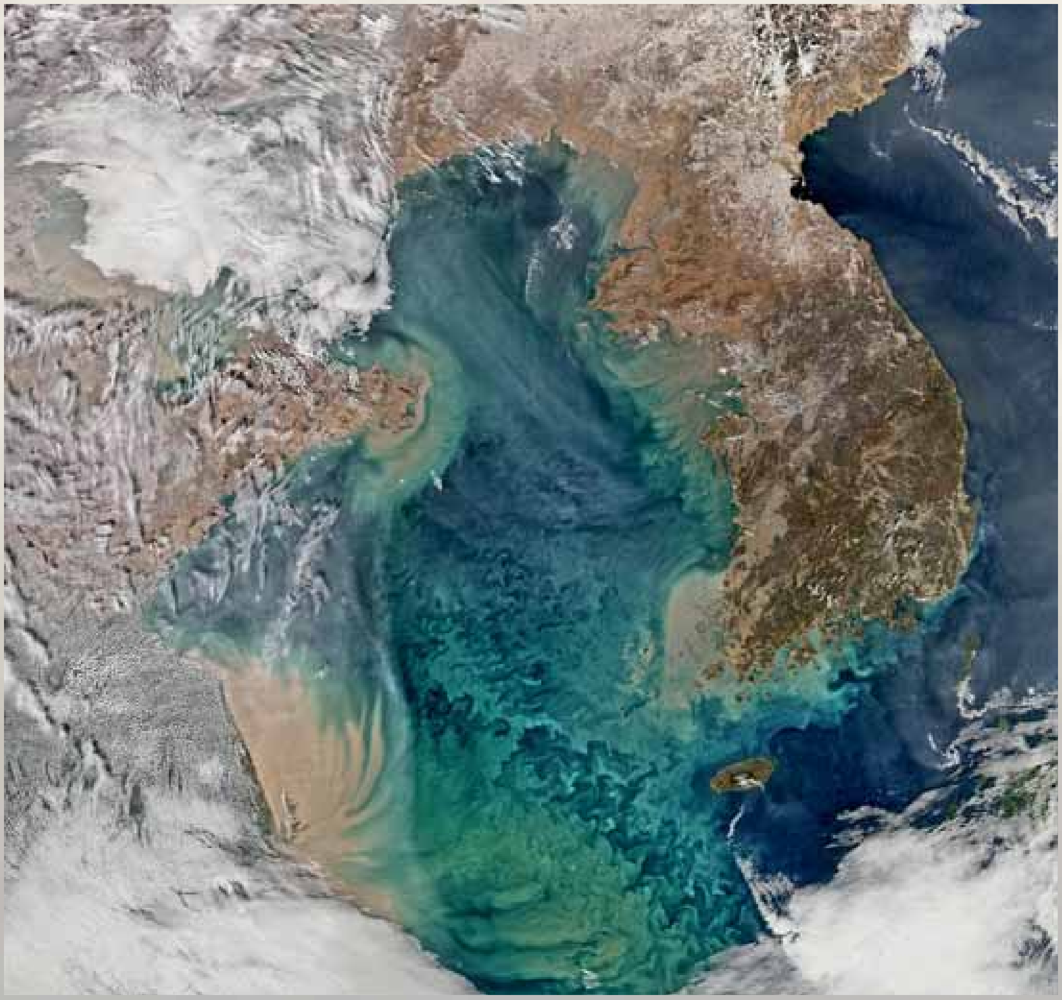
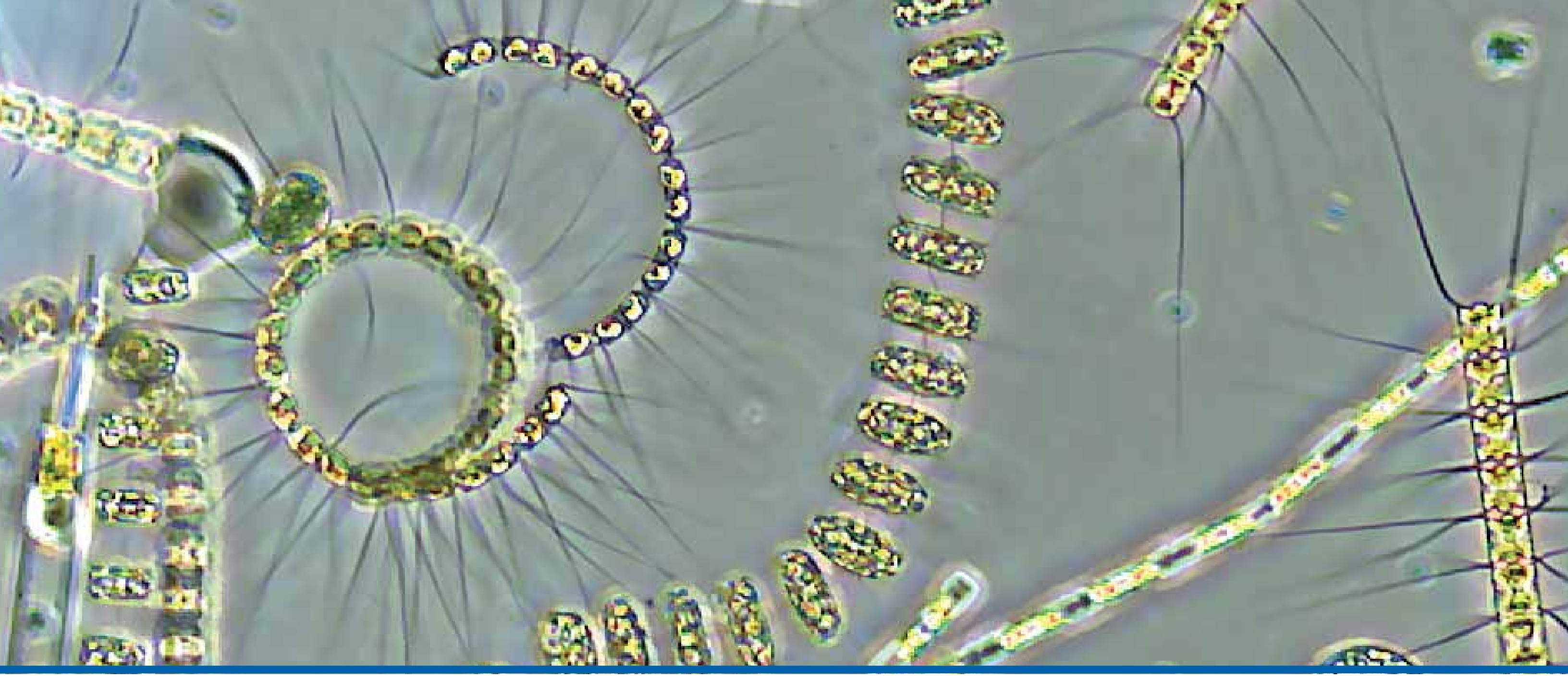
[5]

Highlights

- **Eutrophication in the Yellow Sea is increasing, producing various telltale signs of ecosystem change.**
- **The marine heatwave of 2014–2016 in the Northeast Pacific is associated with lower chlorophyll-a concentrations, smaller phytoplankton, and a record toxic algae bloom.**



Yellow Sea, pictured here in an image acquired on February 24, 2015, by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite.



Chapter 5: Phytoplankton

Authors: Sinjae Yoo and Jeanette C. Gann

Basin-wide changes in satellite chlorophyll-a

To compare mean chlorophyll-a concentrations during the present focal period with those of the previous NPESR report (McKinnell et al., 2010), annual mean chlorophyll-a concentrations from MODIS/Aqua SMI products were extracted for each 9-km pixel and period averages were calculated for 2003–2007, 2008–2013, and 2014–2018. The ratio of mean annual chlorophyll-a in 2008–2013 over 2003–2007 indicates that in the southwestern Bering Sea and Anadyr Bay (PICES region 16), average chlorophyll-a concentrations increased while they decreased in PICES region 17 and along the shelf area in PICES regions 13 and 15 (Figure 5-1). In the Gulf of Alaska and northern California Current region (PICES regions 12 and 11, respectively), average chlorophyll-a concentrations increased during 2008–2013. A decrease occurred in most of the western North Pacific with exceptions in the marginal seas such as PICES regions 20 and 21. In 2014–2018 the pattern reversed, and in most of the western North Pacific average chlorophyll-a concentrations increased (Figure 5-2). In the northern and eastern Bering Sea (PICES regions 14 and 13, respectively), they also increased substantially. However, they decreased in the eastern North Pacific, notably in PICES regions 12 and 11, which may have been related to the marine heatwave in 2014–2016.

Time series of mean annual chlorophyll-a concentrations were extracted from the regions where chlorophyll-a increased or decreased substantially. In the California Current region (PICES region 11), chlorophyll-a increased after 2006 but decreased after 2014 (Figure 5-3). In PICES region 13, concentrations decreased after 2006 but increased after 2014. A similar trend can be seen in the Aleutian Islands (PICES region 15). In PICES region 12, chlorophyll-a change did not show a discernable trend because the change was spatially heterogeneous. During the 2009–2016 focal period, PICES region 14 showed a larger variability between winter–spring seasons. In the western North Pacific, only PICES region 19 showed an increase after 2014.

The interannual changes in these regions resulted from different changes in the seasonal patterns (Figure 5-4). In PICES region 11, the decrease in chlorophyll-a concentrations occurred throughout the year while in PICES region 13, the changes occurred during the spring and autumn blooms. Similarly, the interannual changes resulted from changes in the seasonal blooms in PICES regions 15 and 19. On the other hand, seasonal patterns were generally irregular in PICES region 12.

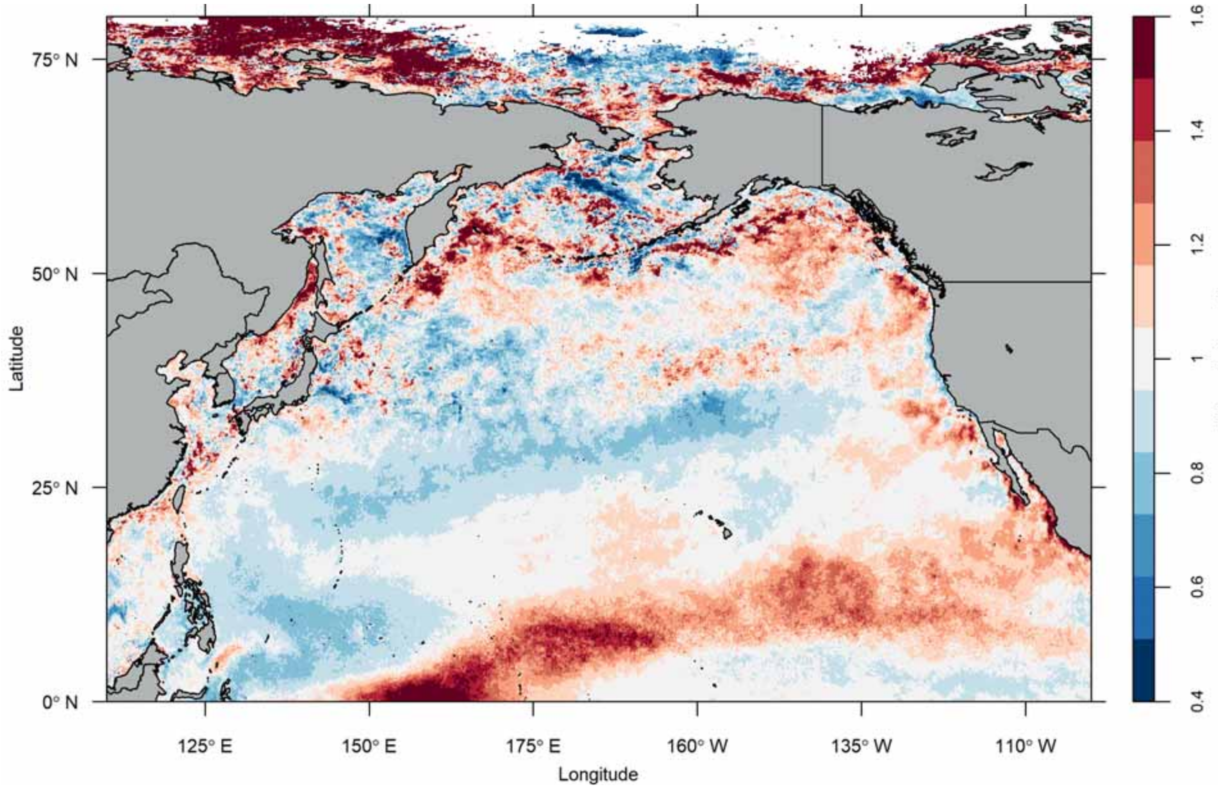


Figure 5-1. Ratio of mean annual chlorophyll-a in 2008–2013 relative to 2003–2007.

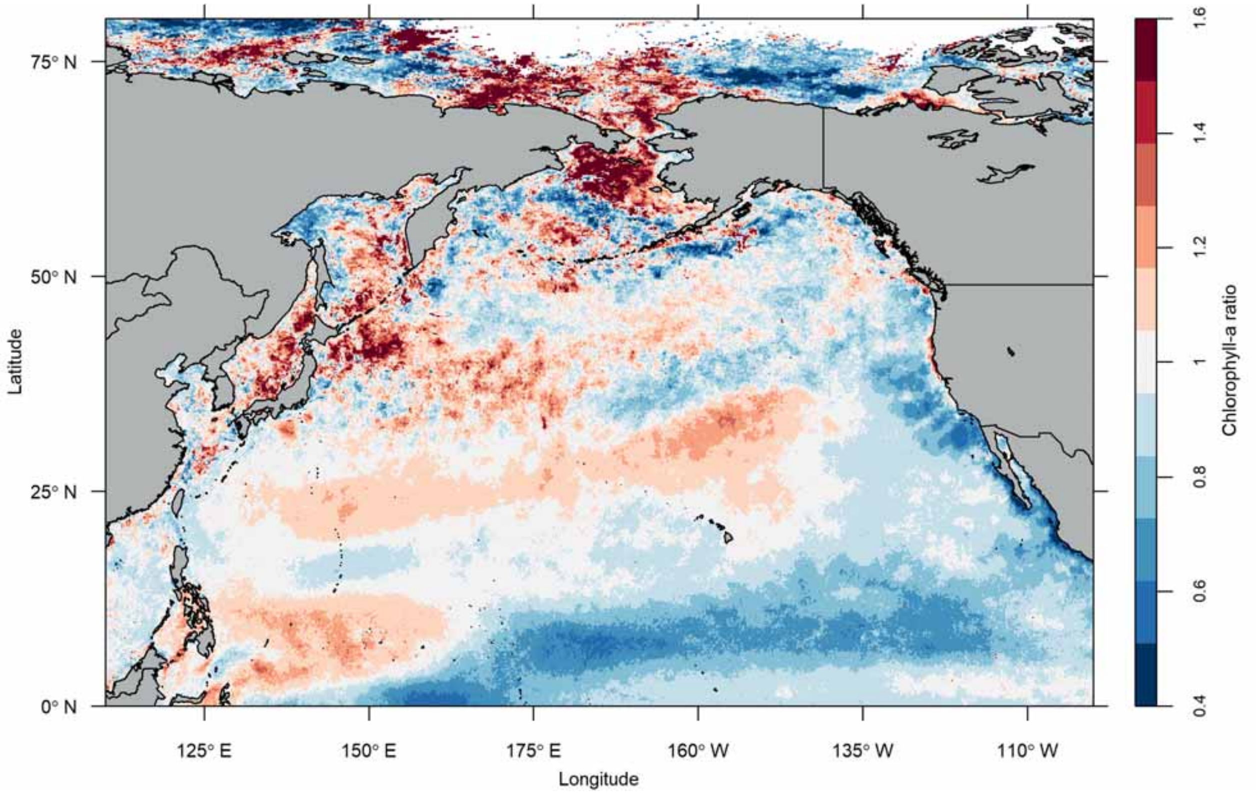


Figure 5-2. Ratio of mean annual chlorophyll-a in 2014–2018 relative to 2008–2013.

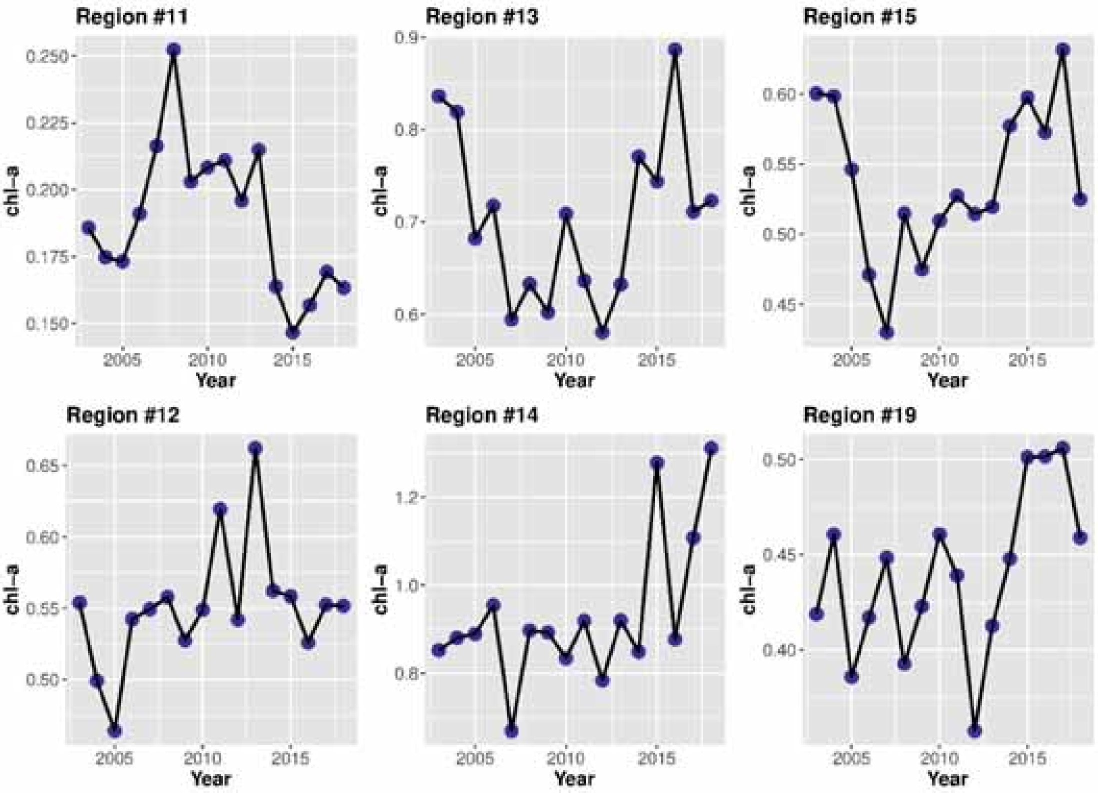


Figure 5-3. Annual mean chlorophyll-a concentrations (mg m^{-3}) in PICES regions showing substantial changes, from 2003–2018.

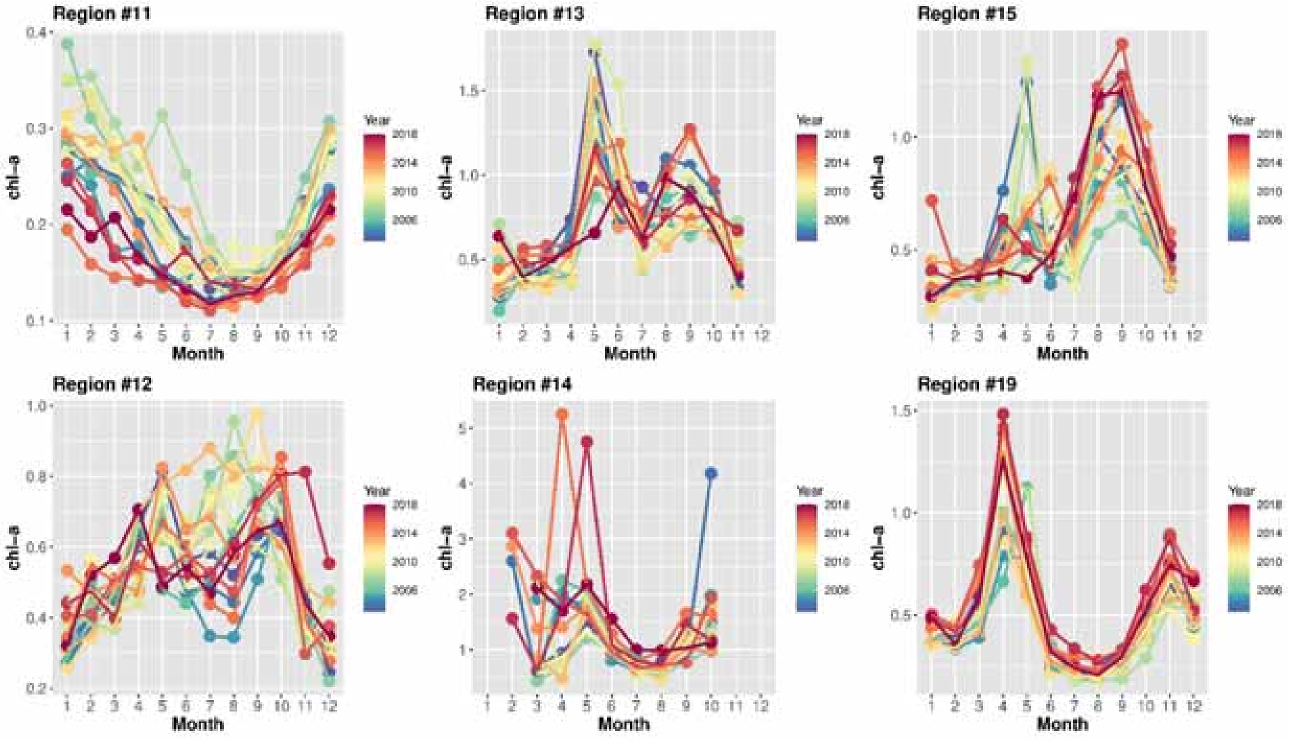


Figure 5-4. Changes in the seasonal patterns of chlorophyll-a concentrations (mg m^{-3}) in the 2003–2018 period for the same regions depicted in Figure 5-3.

Impacts of the 2014–2016 marine heatwave

In contrast to the time period 1997–2007, when phytoplankton increased over expansive areas of the eastern boundary upwelling off the Washington, Oregon, and California coasts in the Northeast Pacific, a prominent trend of low chlorophyll-a concentrations associated with higher temperatures is evident during the latter part of the 2009–2016 focal period. This trend is carried through a number of systems in the Northeast Pacific from southern California up through the northern Bering Sea, and coincides with the significant 2014–2016 marine heatwave often referred to as "the Blob"; see Breakout Box: Northeast Pacific marine heatwave, page 24. Specifically, the southern California Current system saw some of the highest sea surface temperatures (SST) and lowest chlorophyll-a minima ever recorded in coastal and transitional areas (see Chapter 8). Increased temperatures (along with diminished wind mixing events) can lead to a more strongly stratified water column that limits nutrient replenishment from at-depth, thus lowering productivity in the upper water column. Lower spring bloom maxima in the northern Gulf of Alaska were seen during later, warmer years in the time series coinciding with fewer large diatom species (Figure 5-5; Zador and Yasumiishi, 2018). A similar pattern of lower chlorophyll-a and smaller phytoplankton was also seen over the eastern Bering Sea shelf (north and south), where lower concentrations of chlorophyll-a in the large size fraction (>10 µm) during 2014 and 2015 suggests fewer large diatom species, thought to be important as a nutritional component in the ecosystem, were present (Figure 5-6; Siddon and Zador, 2018). Conversely, an increase in diatoms was seen off the coast of British Columbia during the same time period (2009–2015) via Continuous Plankton Recorder surveys, although the reasons remain unclear.

Wind mixing and chlorophyll-a

Wind mixing related changes in chlorophyll-a concentrations were noted for two separate North Pacific regions (PICES regions 23 and 13). Diminished wind mixing events can be associated with greater ocean stratification, relating to a shallower mixed layer depth (MLD) and decreased flux of nutrients to the surface, thus limiting production (Eisner et al., 2016). This direct relationship is shown within the southeastern part of PICES region 13 (Figure 5-7; Siddon and Zador, 2018, see Chapter 7). However, in the western North Pacific (PICES region 23), chlorophyll-a had a varied response to deeper MLD via an increase in chlorophyll-a concentrations with a deeper MLD over some areas, and a decrease in concentrations with a deeper MLD in others (NPESR3, PICES region 23 report[1]).

Expansion of low surface chlorophyll-a in the central North Pacific

Low surface chlorophyll-a (≤ 0.07 mg m^{-3}) areas are known as oligotrophic regions, and are a major feature of the subtropical North Pacific between 5°N and 25°N. From 1997 to 2008, the oligotrophic region has expanded by about 2% per year, a rate which is comparable with similar observations in the South Pacific, North Atlantic, and the South Atlantic (Polovina et al., 2008). The expansion of the oligotrophic region is consistent with a global warming pattern of increased vertical stratification of the ocean. Using similar criteria as Polovina et al., (2008), the area of the oligotrophic region was calculated for October–December from 2003–2018 MODIS/Aqua data (Figure 5-8). The linear regression between the time and the oligotrophic area was significant ($p = 0.0076$). The rate of increase was 127,492 km^2 yr^{-1} (0.67% yr^{-1}). However, the oligotrophic region did not expand during the period 2014–2018.

Anthropogenic eutrophication in the western North Pacific

The marginal seas in the western North Pacific are under increasing anthropogenic pressure. The Yellow Sea and northern East China Sea (PICES regions 20 and 21) receive a large amount of nutrients via wet and dry deposition through air (Chen et al., 2010; Kim et al., 2011), river runoffs (Yuan et al., 2008; Zhou et al., 2010; Li et al., 2015; Liu et al., 2018), and from submarine ground water discharge (Tan et al., 2018; Wang et al., 2018), all of which have intensified over the past decades. The annual means of chlorophyll-a concentration and primary productivity in the Yellow Sea steadily increased after 2000 and leveled off in 2008–2011 (Yoo et al., 2019). The PICES region 20 ecosystem has been dominated by anthropogenic pressure, as this pattern is not associated with any climate pattern.

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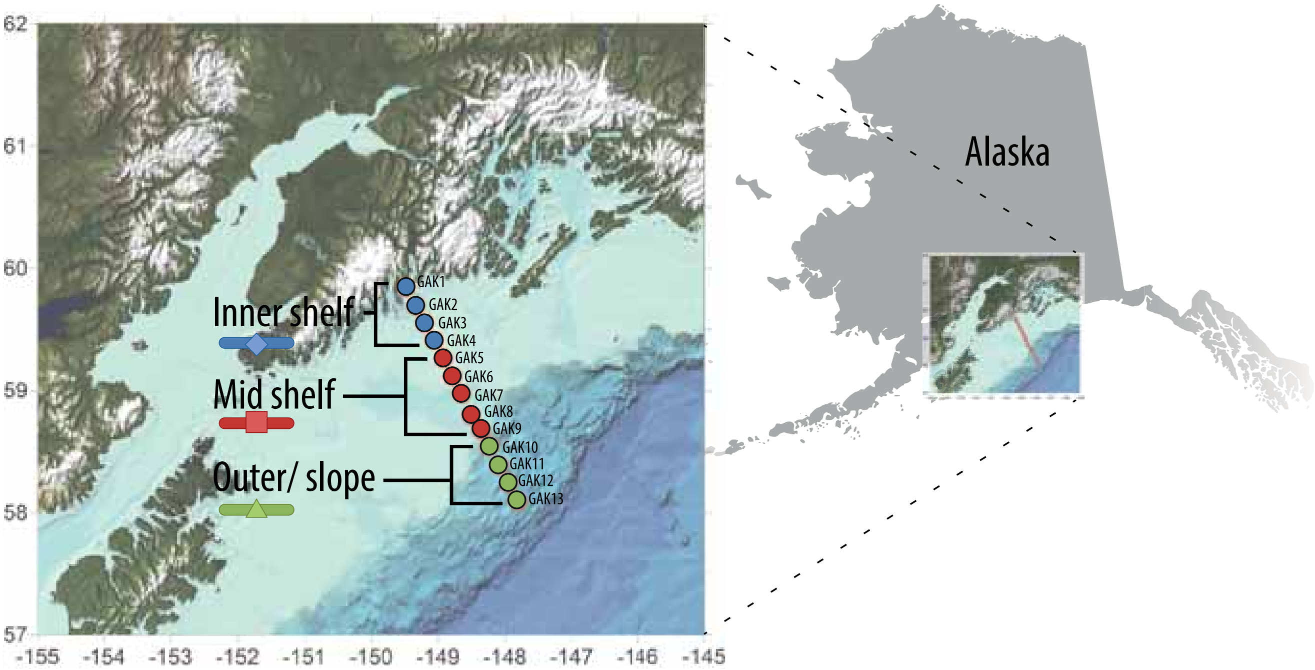
[1] https://meetings.pices.int/publications/special-publications/NPESR/2021/2021_PICES_NPESR3_Region23.pdf



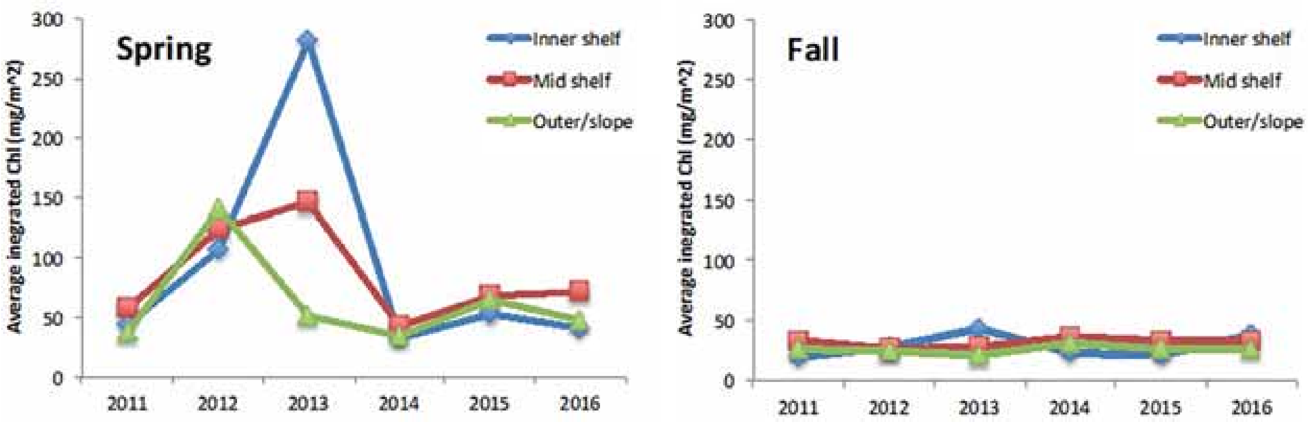


Figure 5-5. Gulf of Alaska mean values of seasonal integrated chlorophyll-a by shelf zone (inner = GAK 1–4; mid = GAK 5–9; outer = GAK 10–13) in spring and fall.

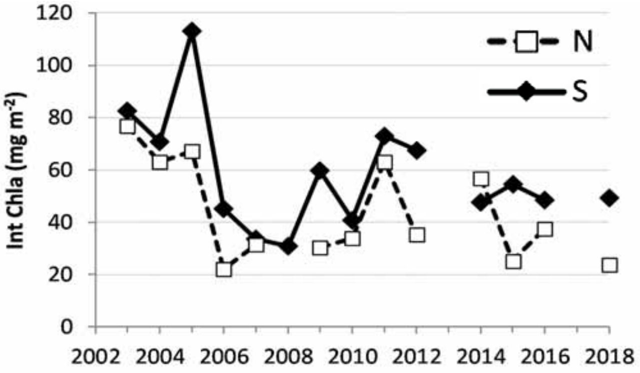


Figure 5-6. Integrated chlorophyll-a concentrations and integrated large size fraction chlorophyll-a (>10 µm), over the north and southeastern Bering Sea shelf.

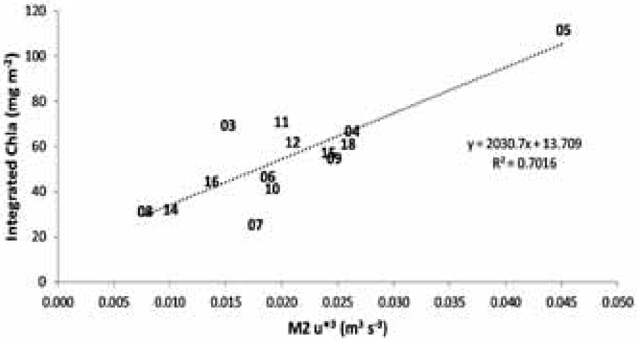
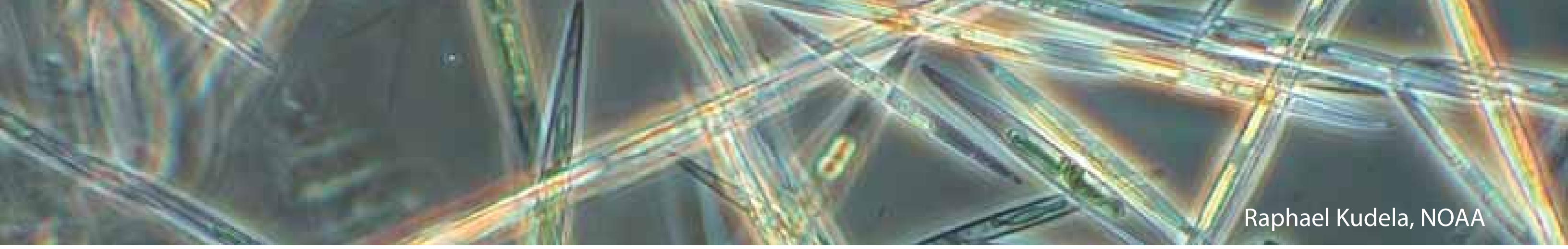


Figure 5-7. Direct relationship between wind mixing (u^3, $m^3 s^{-3}$) and integrated chlorophyll-a (mg m^{-2}), $R^2 = 0.70$. Numbers represent years: 2003 (03) to 2018 (18), excluding 2013 and 2017.


Raphael Kudela, NOAA

Harmful algal blooms

An unprecedented bloom of *Pseudo-nitzschia*, a toxin-producing diatom, occurred across the majority of the Northeast Pacific coast from southern California all the way up to the Gulf of Alaska during 2015. The unusual toxic bloom in PICES region 12 coincided with the significant marine heatwave covering the same area. The domoic acid toxin produced by *Pseudo-nitzschia* was measured in a number of stranded marine mammals, and the event triggered the closure of numerous fisheries along the west coast of the USA, including razor clam, rock crab, and Dungeness crab (McCabe et al., 2016; Zhu et al., 2017). A series of strong spring storms concentrated the *Pseudo-nitzschia* near the coast, where conditions were ideal for growth (anomalously warm temperatures, and higher nutrients brought up from the deep ocean by seasonal upwelling). This allowed the bloom to expand its scale considerably, with maximum growth rates, and enhanced toxin production (McCabe et al., 2016).

Due to increasing eutrophication within the marginal seas of the western North Pacific, the frequency of harmful algal blooms (HABs) has been increasing in recent decades. Also, the causative species have altered, with more dinoflagellate species seen in more recent years. The increase in the N:P ratio in the vicinity of the Changjiang River mouth has led to an increase in dinoflagellate blooms. In PICES region 20, the frequency of algal blooms had increased between 2000 and 2010 both in Chinese and Korean coastal waters. However, the frequency decreased after 2010 (see PICES region 20 report[1]). The decrease in the frequency of HABs under progressing eutrophication may be related to potential factors such as the decrease in the water temperature or increased zooplankton grazing, and requires further investigation.

Shifts in phytoplankton taxa and morphology with changing environmental conditions

Offshore conditions like those in PICES region 24 have shown a predominance of haptophytes and smaller phytoplankton cells in general. This area is also typically characterized by a high nutrient low chlorophyll (HNLC) scenario where iron is often presumed to be the limiting nutrient for growth. Chorophyll-a concentrations over a long time series (2000–2016) remain relatively stable, while shifts in underlying community composition of phytoplankton occur with varying environmental conditions. Continuous Plankton Rrecorder data in PICES region 24 (offshore NE Pacific) were analyzed for diatom taxa and differentiated between morphotypes of round centric versus small thin diatoms (Boldt et al., 2019). A time series from 2000–2016 spans two warm periods (2002–2005 and 2014–2016) on either side of a cooler period, with smaller and thinner morphotypes of diatoms more prominent during warmer periods. The 2015 extreme warm event is evidenced by a significant shift from round to thin diatom types (see Figure 5-9), suggesting the larger surface area to volume ratio in thin diatom morphotypes have a better advantage during times of decreased nutrient availability.

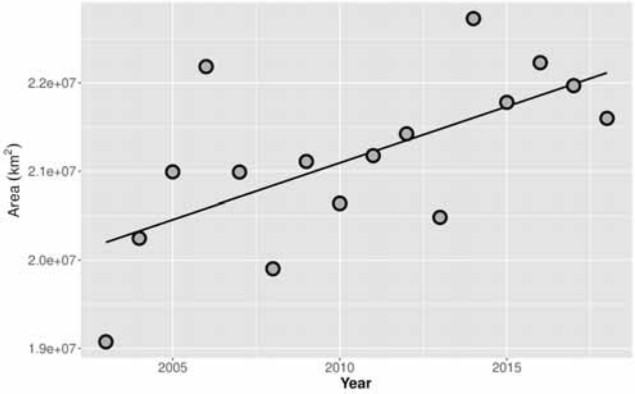


Figure 5-8. Time series and regression line for the oligotrophic area (where surface chlorophyll-a ≤ 0.07 mg m^{-3}) in the North Pacific in October–December using 2003–2018 MODIS/Aqua data.

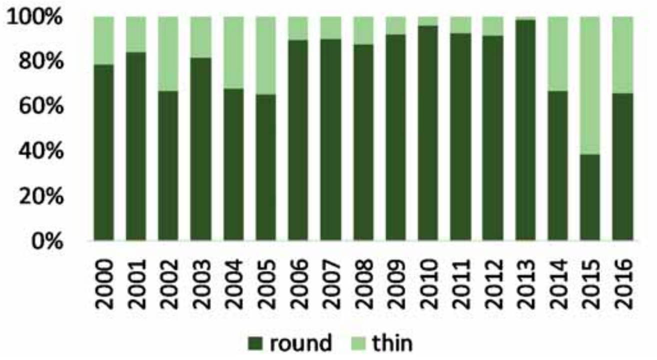


Figure 5-9. Percent composition of diatom morphology (round vs thin) in PICES region 24 from 2000–2016.

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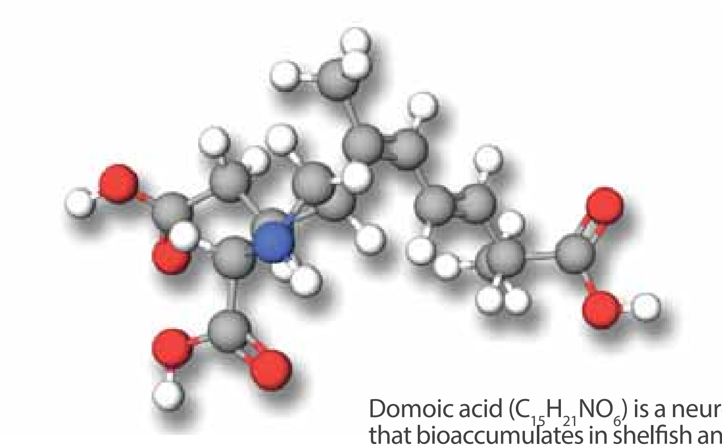
[1] https://meetings.pices.int/publications/special-publications/NPESR/2021/2021_PICES_NPESR3_Region20.pdf



Model: Lori Waters.

Domoic acid ($C_{15}H_{21}NO_6$) is a neurotoxin produced by the diatom *Pseudo-nitzschia* that bioaccumulates in shellfish and fish. When fish and shellfish contaminated with this neurotoxin are consumed by animals, including people, poisoning may result, which can cause seizures, brain damage, memory loss and, in some cases, death.

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[6]

Highlights

- **Zooplankton variability is more evident as composition rather than abundance changes; warm water zooplankton taxa have shown increases in abundance and/or a northwards extension.**
- **Gelatinous zooplankton became more abundant in the Northeast Pacific and Bering Sea during the 2009–2016 focal period, but the extraordinary jellyfish blooms noted in the western regions in the second version of the North Pacific Ecosystem Status Report were absent.**

Top row, L-R: *Caliopus pacificus*; *Paraeuchaeta* with eggs. Middle row, L-R: *Stilipes distincta*; *Cyphocaris challengeri* oceanic; *Euphausia pacifica* male. Bottom row, L-R: *Scrippsae*; *Thysanoessa spinifera*; *Thalia democratica*. Photos: Moira Galbraith.

Tamara Fraser

Chapter 6: Zooplankton

Authors: Sonia D. Batten and Kazuaki Tadokoro

Introduction

Zooplankton are the intermediaries between primary production and higher trophic level fishes, marine birds and mammals. There are three main size classes of zooplankton, with each class having somewhat different trophic roles and requiring different sampling strategies.

The smallest organisms, the microzooplankton, are mostly single-celled protists or very small metazoans with sizes and turnover rates quite similar to phytoplankton (on the order of about one day). They are important grazers of primary production, particularly in oceanic areas, but time series with adequate spatial and/or temporal resolution to understand their dynamics are rare.

The mesozooplankton are those organisms in the size range from about 200 µm to about 1 cm and comprise taxa that spend their entire life cycle in the plankton (e.g., copepods, chaetognaths, pteropods) as well as the larval stages of many benthic invertebrates (e.g., crabs, shellfish, echinoderms) and fishes which may only be planktonic for a short time period. The mesozooplankton are a diverse group with many different life histories (from a few weeks to a few years) and feeding modes (may be herbivorous, carnivorous, mucus net feeders) but are the group that comprises most of the time series presented in this report. Many species also undergo significant vertical migrations (potentially hundreds of meters) which may be daily or seasonal (ontogenetic) so that there is considerable variability in time spent in surface waters where they are most available to their predators.

The third group, the macrozooplankton, are larger than 1 cm, and in the case of the largest jellyfish, can reach up to 2 m in diameter. Owing to their large size and/or greater swimming ability, they are challenging to sample so there are also few adequate time series of this group.

Even within each group, sampling methodology and analysis and, consequently, metrics of abundance reported, vary by region with differing degrees of taxonomic resolution and units of density. This makes direct comparisons between regions more challenging. For the most part, however, interannual variability in total abundance or biomass is much greater than any trend during the 2009–2016 focal period. Where trends are evident, they occur as community composition changes, suggesting that diversity is more responsive to forcing than overall density.

Individual regional reports of NPESR3 describe the local variability in zooplankton abundance or biomass, which in many cases is broken down into groupings of taxa with similar functional roles, or indicator groups, depending on the resolution of the data. However, there were two major themes that spanned the North Pacific during the 2009–2016 focal period which are described in more detail below.

Expansion of warm water taxa

Zooplankton observations for many of the PICES regions report either an increase in species more typically associated with warmer, southern waters and/or a northward expansion during 2009–2016. This is an important response of the zooplankton community to physical forcing since the nutritional value of warm water taxa to the food web is believed to be poorer than that of cold water taxa; they are typically smaller in size (so more work is required for a predator to meet its nutritional needs), and they have less lipid (storage of lipid is associated with overwintering strategies in subarctic copepod taxa) so have fewer calories and are less nutritious. In addition, a longer food chain is required when smaller planktonic organisms are present, and energy transfer losses occur at each step in the food chain (because of respiration) so the result is less production available to the upper trophic levels.

In the Northeast Pacific the increase in warm water taxa was primarily driven by the marine heatwave of 2014–2016 (Bond et al., 2015) which produced significantly elevated sea

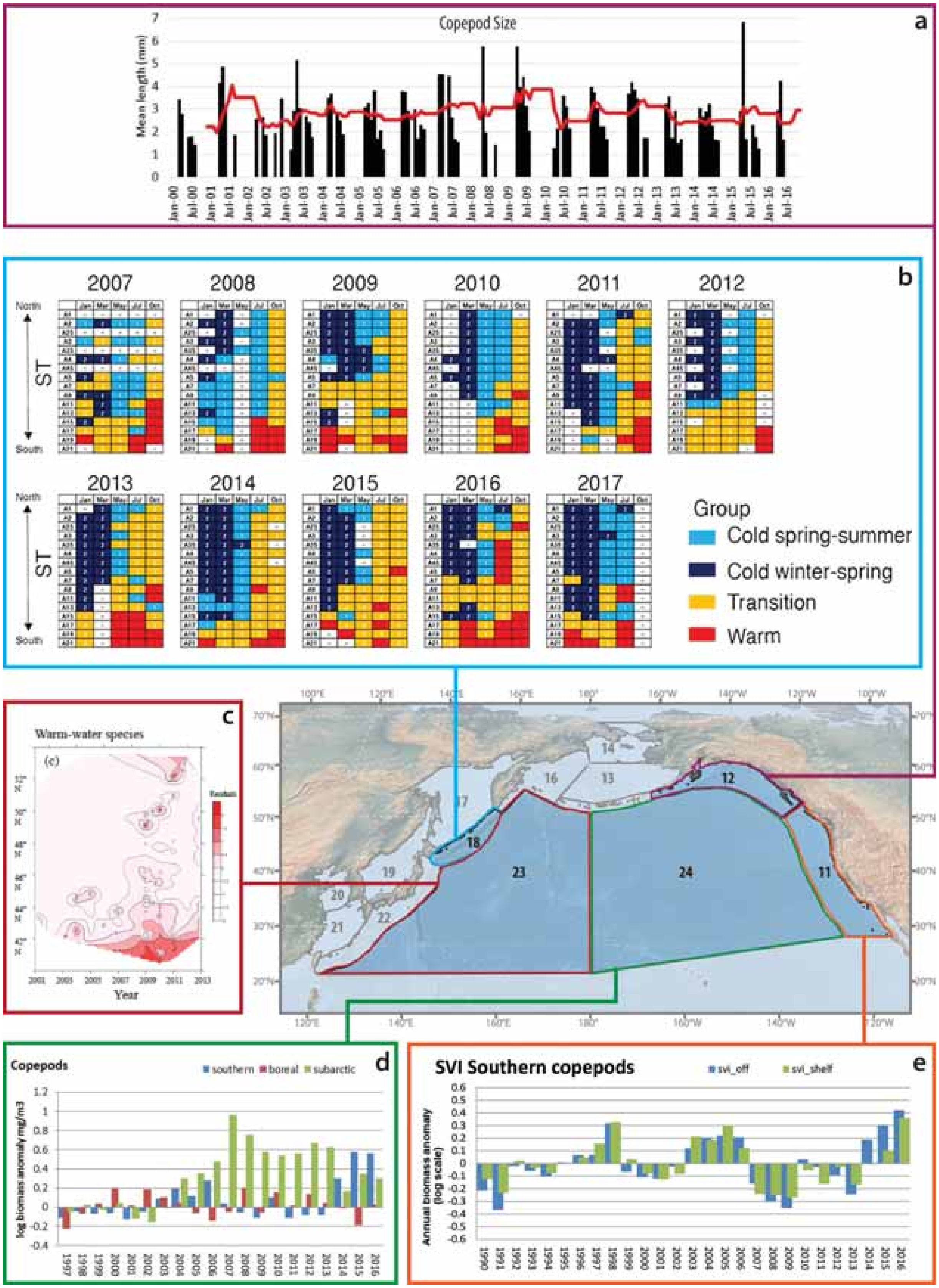

Figure 6-1. Anomalies of warm water species abundance for PICES regions 11 (southern Vancouver Island), 12, 18, 23 and 24.

surface temperatures (SST) from California to Alaska (see Breakout Box: Northeast Pacific marine heatwave, page 24). Several time series in the California Current system report mesozooplankton changes – positive anomalies in southern copepods from fall 2014 along the Newport Hydrographic Line off central Oregon (Peterson et al., 2017) and in 2014–2016 off Vancouver Island (Panel e in Figure 6-1), and a shift to smaller copepod taxa from 2013–2015 on the southern British Columbia shelf (mean copepod size from Continuous Plankton Recorder (CPR) data). In the Alaska Current system negative anomalies in mean copepod size also occurred from 2013 to 2016 on the western Gulf of Alaska shelf (Figure 6-1, panel a; Batten et al., 2018). The oceanic Northeast Pacific (PICES region 24) showed similar patterns with positive anomalies of southern copepod (Figure 6-1, panel d) and southern chaetognath taxa from 2014–2016, so it is clear that the marine heatwave caused a simultaneous basin-wide change in zooplankton community composition, with a higher proportion of southern, typically smaller, taxa with reduced caloric content.

In the Bering Sea regions, particularly the wide shelf in Region 13, the impacts of warm conditions on the zooplankton are reflected as changes in the relative abundance of taxa rather than appearance or disappearance of warm or cold water species. The timing of sea ice retreat determines the type and timing of the phytoplankton bloom; an early ice retreat triggers a later open water bloom while a late ice retreat leads to an earlier bloom associated with the ice edge. The latter situation is beneficial for large to medium sized copepods and euphausiids while the former favours smaller copepod species that benefit from the warmer waters (Hunt et al., 2011). This region saw a switch from cold to warm conditions in 2014 but the zooplankton response (based on quite sparse CPR data from deep waters) was modest, with a small increase in abundance and a small decrease in mean size (see the PICES region 13 report[1]).

Although there was no marine heatwave event as such in the western Subarctic Gyre, there have been significant increases in SST over much of the region (see Figure 3-4). A northward shift in the centre of distribution and an increase in abundance of warm water copepods from 2009 onwards in CPR samples was significantly correlated with SST (see panel c in Figure 6-1). In the Oyashio region (PICES region 18), the zooplankton communities identified as "warm" and "transition" expanded northward in 2015 and 2016, (Panel b in Figure 6-4) years that exhibited increased sea surface temperatures and salinity. It seems, therefore, that the latter part of the focal period saw an increase in warm water zooplankton that spanned the entire width of the North Pacific Ocean.

Patterns in gelatinous zooplankton

Gelatinous zooplankton, classified as Cnidaria and Thaliacea, are included here. Because of their fragility and sometimes large size, these groups are difficult to quantitatively sample with some traditional samplers such as the CPR and so some regions have limited information. However, other surveys do assess gelatinous plankton routinely. Both groups have been surveyed in the Northeast Pacific (PICES regions 11,12 and 24) and in the eastern Bering Sea (PICES region 13).However, Cnidaria was the main group surveyed in the western side of the North Pacific (PICES regions 19 and 20), especially for assessing abundance of giant jelly fish (e.g., *Nemopilema nomurai*).

In the Northeast Pacific the pattern of year-to-year variation of gelatinous zooplankton biomass is different between the south and north. Thaliacea and Cnidaria had low biomass from 2000 to the mid-2000s off Baja California (PICES region 11), followed by an increase and sustained high values until the early 2010s. After that, the biomass decreased through the 2009–2016 focal period. Conversely, Cnidarian biomass was low in the northern part of the region (south of Vancouver Island up to the Gulf of Alaska coast in PICES region 12) in the early 2000s and at the start of the focal period but was higher during the remainder of the period. In the eastern Bering Sea (PICES region 13), although different species showed differing patterns, overall biomass generally had high values in the early to mid-2000s, followed by a decline and then an increase during the focal period. The wide-scale synchronicity of the patterns of year-to-year variation of the gelatinous zooplankton biomass in the eastern regions suggests that environmental conditions, (e.g., increased temperatures) may be responsible.

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[1] https://meetings.pices.int/publications/special-publications/NPESR/2021/2021_PICES_NPESR3_Region13.pdf

Table 6-1. Summary of gelatinous zooplankton trends in each region from 2000 to 2018.

PICES regions				**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
11	Southern British Columbia	N. Vancouver Island shelf	Cnidarians	–	+	+	+	+	+	+	+
		N. Vancouver Island offshore	Cnidarians	+	+	+	+	+	+	+	+
		S. Vancouver Island shelf	Cnidarians	+	–	+	–	+	+	+	+
		S. Vancouver Island offshore	Cnidarians	–	–	–	–	–	+	+	+
		SST							warm	warm	warm
13	Eastern Bering Sea		Staurophora	–	–	–	–	–	–	–	+
			Phacellophora	–	–	–	–	–	–	+	–
			Cyanea	–	–	–	–	–	–	–	+
			Chrysaora	–	+	+	+	+	+	+	–
			Aurelia sp.	–	–	–	–	–	–	–	+
			Aequorea	–	–	–	–	–	–	+	+
14	N. Bering Sea		N/A								
15	Aleutian Islands		N/A								
16	W. Bering Sea		N/A								
17	Okhotsk Sea		N/A								
18	Oyashio		*Doliolium* spp.	–	–	–	–	+	+	+	+
19	coastal Japan		giant jelly fish	+	–	–	–	–	–	–	–
20	E. Yellow Sea		giant jelly fish	N/A	N/A	N/A	–	–	–	N/A	–
			Medusae	+	–	–	+	–			
21			N/A								
22			N/A								
23			N/A								
24	Oceanic NE Pacific	Line P	N/A	–	–	–	–	–	+	+	+

Green plus signs (+): increasing levels
Red minus signs (–): decreasing levels
N/A: not available

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On the western side of the Pacific, the biomass of the giant jellyfish *N. nomurai* showed low values in 2000–2001 but then it increased, and from 2003 high values were maintained until 2009 in the coastal waters of Japan (PICES regions 19 and 20). These large jellyfish blooms were thus a significant phenomenon in the previous NPESR (McKinnell et al., 2010) and further information can be found in Uye and Brodeur (2017). However, during much of the period of this current report (2010 onwards), such large blooms have been absent. Biomass in Korean coastal waters of the Yellow Sea, which is a reproductive area for this species (e.g., Kawahara et al., 2006), showed a similar pattern to that in the coastal waters of Japan. This suggests that reproductive success in the Yellow Sea is important to the recruitment of *N. nomurai* in Japanese waters. Other cnidarian species showed different patterns of year-to-year variation of biomass in part of PICES region 20. In PICES region 18, Thaliacea had high biomass in 2013–2016, which were high SST years.

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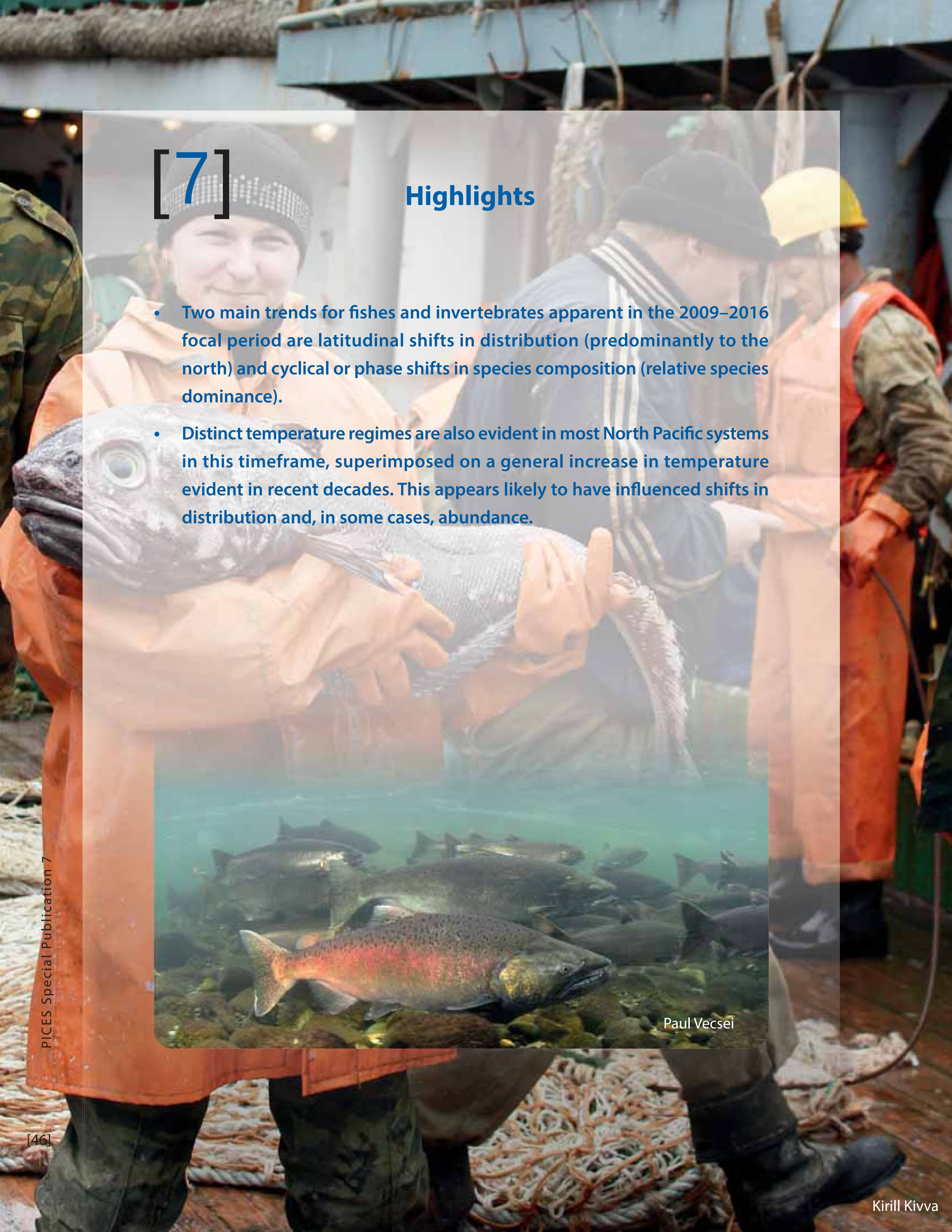

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Highlights

- Two main trends for fishes and invertebrates apparent in the 2009–2016 focal period are latitudinal shifts in distribution (predominantly to the north) and cyclical or phase shifts in species composition (relative species dominance).
- Distinct temperature regimes are also evident in most North Pacific systems in this timeframe, superimposed on a general increase in temperature evident in recent decades. This appears likely to have influenced shifts in distribution and, in some cases, abundance.

Paul Vecsei

Chapter 7: Fishes and Invertebrates

Authors: Matthew R. Baker and Elizabeth C. Siddon

Introduction

Across the North Pacific, fish and invertebrate populations have shown shifts in distribution in response to broad-scale changes in ocean temperatures. The dynamics of fish and invertebrate species that rely on the pelagic environment during their life history may be particularly responsive to environmental drivers (e.g., temperature) as well as biological drivers, (e.g., prey, production, inter-specific competition). Improved mechanistic understanding of population responses to climate variability is vital for evaluating past trends and forecasting projections of species and stock responses to environmental forcing. Individual species show differential responses, but commonalities among functional groups enable pan-Pacific comparison of responses to ecosystem shifts during the 2009–2016 focal period of this report.

Two main trends for fishes and invertebrates apparent in the focal period are:

1. latitudinal shifts in distribution;
2. cyclical or phase shifts in species composition.

The Kuroshio–Oyashio systems (PICES regions 18 and 22) and the California Current (PICES region 11) encompass large latitudinal contrasts of environments. In both of these geographic areas, recent biomass patterns and commercial catches in small pelagic fishes indicate decadal changes and/or alternations in dominant species or species replacements. Although the mechanisms of species replacements are not fully resolved, ocean–climate regime shifts together with species interactions have clearly had profound impacts on the dynamics of fish community composition and species dominance, particularly among small pelagic species.

Distinct temperature regimes are evident in most North Pacific systems in this timeframe, superimposed on an increase in temperature generally. This has caused shifts in distribution and, in some cases, abundance. The northernmost part of the North Pacific (Bering Sea and Aleutian Islands, PICES regions 13, 15, 16) experienced cold oceanographic conditions between 2007–2013 and in 2014 transitioned to a new warm stanza that persisted through 2015. The impact of this transition was observed at multiple trophic levels within the Bering Sea. Also, in the Northeast Pacific (PICES regions 11 and 12), a large-scale and extensive marine heatwave was observed in 2014–2016 that altered fish and invertebrate dynamics throughout the western Pacific.

Many of the datasets in this chapter borrow from data collected as surveys and assessments or from commercial catch data. Trends in fish and invertebrate biomass may be indicative of trends in pelagic or benthic production or may suggest a response to variability in the overall marine environment. Data derived from commercial fisheries and catch biomass may also indicate trends in levels of exploitation, related not only to stock biomass but also economics.

Forage fish

Exemplar forage fishes within the North Pacific include sardines and pilchards (*Sardinops* spp.), anchovies (*Engraulis* spp.), mackerels (*Scomber* spp.), Pacific herring (*Clupea pallasii*), capelin (*Mallotus villosus*) and sand lance (*Ammodytes* spp.). Within large marine ecosystems, these species represent an ecologically significant niche, influencing both bottom-up and top-down trophic pathways. The predominant species vary across ecosystems, and in species common to multiple regions there appear to be differential and asynchronous dynamics and interactions in various geographical regions, demonstrating that drivers of population dynamics vary from western to eastern Pacific systems.

The Kuroshio system (PICES region 22) provides spawning and nursery grounds for several forage fish species, including Japanese sardine (*Sardinops melanostictus*), Japanese anchovy (*Engraulis japonicus*), round

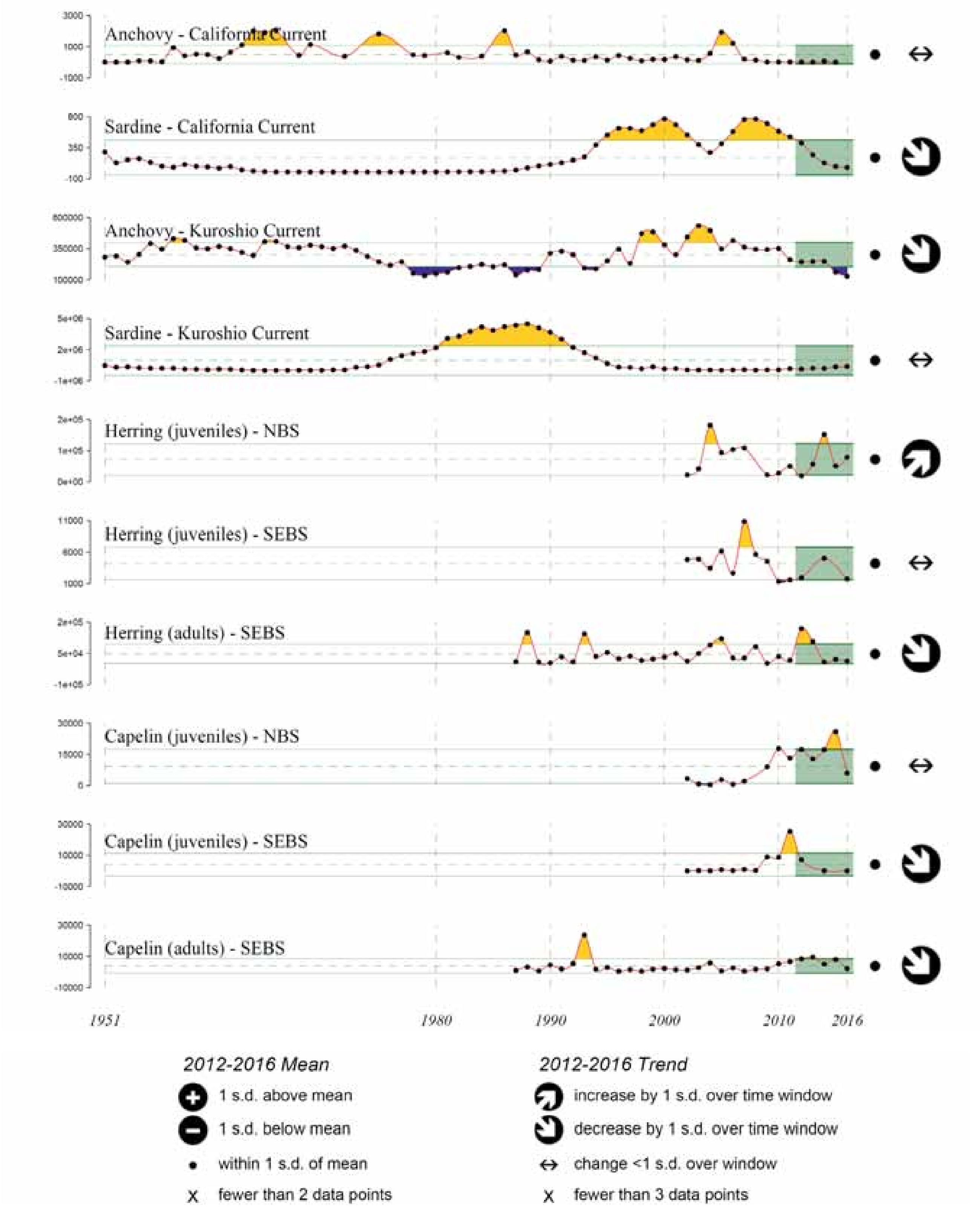

Figure 7-1. Trends in exemplar forage species for the California Current (data: Sydeman et al., 2020), Kuroshio (data: Kazuaki Tadokoro, personal communication[1]), southeastern Bering Sea (SEBS) and northern Bering Sea (NBS) (data, Siddon and Zador, 2018) ecosystems.

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[1] Kazuaki Tadokoro, Fisheries Resources Institute, Marine Environmental Division, Japan Fisheries Research and Education Agency.

herring (*Etrumeus teres*), mackerel (*Scomber* spp.), and Pacific saury (*Cololabis saira*). Out-of-phase population oscillations occur in this region between sardine and anchovy (Takasuka et al., 2007; Saito, 2019). Broadly, during Pacific Decadal Oscillation (PDO)-positive phases, ocean temperatures in the western Pacific are cooler and sardine populations dominate the community composition. During PDO-negative phases, water temperatures are warmer and anchovy dominate. Since the late 1980s, Kuroshio Current sardine have suffered very low population levels (Figure 7-1). Recently, however, sardine numbers have started to increase, showing a sign of their population recovery (Yatsu, 2019; Takasuka et al., 2021). In contrast, the population levels of anchovy are now declining. There is also evidence of an eastward shift in the center of gravity of Pacific saury distribution after 2010 (Hashimoto et al., 2020).

As such, the pelagic fish community in the Kuroshio Current system may be experiencing a shift to a new regime. Bottom-up drivers have been proposed for sardine population dynamics; deeper winter mixed layer depth leads to spring phytoplankton blooms in the nursery grounds. Also, differential optimal temperatures for growth rates during the early life stages as well as for spawning between anchovy and sardine provide an explanation for these species alternations (Sugimoto et al., 2001; Tadokoro et al., 2005; Takasuka et al., 2008a, Nishikawa et al., 2011, 2013; Okazaki et al., 2019; Oozeki et al., 2019).

In the eastern Bering Sea (PICES region 13) and northern Bering Sea (PICES region 14), climate variability has impacted the spatial extent of seasonal sea ice (Danielson et al., 2011; Baker et al., 2020), leading to changes in community composition (e.g., zooplankton, Eisner et al., 2014, 2018; fish, De Robertis and Cokelet 2012; Kotwicki and Lauth 2013; Duffy-Anderson et al., 2017; Siddon et al., 2018) and trophic dynamics (Stabeno et al., 2010). Two key forage fish species in the system are capelin and Pacific herring. The biomass of both species is greater in the northern areas (Wilson et al., 2016), but shifts in distribution and abundance occur in response to above- and below-normal thermal conditions (i.e., warm and cold years; Parker-Stetter et al., 2016). During the previous warm (2003–2005) and cold (2006–2011) stanzas, capelin biomass increased from the warm years to cold years with concomitant expansion of their distribution over the eastern shelf


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(Hollowed et al., 2012; Baker and Hollowed, 2014). During that same time period, changes in Pacific herring biomass were less evident (although increased from warm to cold years), but the population contracted northward over the northern shelf (Andrews et al., 2016). In the 2009–2016 focal period, the shelf area of PICES region 13 experienced a shift from cold to warm conditions with the transition occurring around 2013 (Stabeno et al., 2007). During the cold years, capelin biomass was high, especially in the north, with a strong decline after 2015 (Figure 7-1). Concurrently, herring biomass was higher in the northern areas, demonstrating a similar range contraction as the previous cold stanza (Figure 7-1).

In the Gulf of Alaska (PICES region 12), capelin abundance increased sharply in 2007, then decreased in 2014 and 2015. The increase in abundance coincided with cooler years, consistent with patterns observed in PICES region 13 and abundance decreased with the onset of the marine heatwave (2014–2016; Logerwell et al., 2010; McGowen et al., 2019).

Both sardine and anchovy were present in the California Current ecosystem between 1990–2015; prior to 1990 sardine were low due to overfishing. In this system, there is evidence that sardine and anchovy respond to different environmental cues and may not exhibit out-of-phase oscillations (Barange et al., 2009; MacCall, 2009; Ruzicka et al., 2012; Lindegren et al., 2013; Fiechter et al., 2015). In the mid-2000s, Pacific sardine (*Sardinops sagax*) decreased and anchovy increased, which may have been related to environmental factors. Increased upwelling and reduced temperatures have been linked to positive responses in northern anchovy (*Engraulis mordax*; Checkley et al., 2017); in 2000–2002 anchovy showed positive trends while trends turned negative in 2003–2005 (Rykaczewski and Checkley, 2008). The decline in sardine was largely due to fishing (Hill et al., 2012). After 2009, abundance declined for both species, such that northern anchovy remained at low levels and sardine demonstrated a downward trend from 2009 through 2015 (Sydeman et al., 2020). Several forage fish species demonstrated dramatic reductions in condition and energy content in the context of North Pacific anomalous warming (2014–2016) in the California Current and Gulf of Alaska (Baker et al., 2019; Thompson et al., 2019; von Biela et al., 2019).

(*Sebastes* spp.)

Groundfish

In the Gulf of Alaska (PICES region 12), widespread declines in fish biomass were observed among species from 2013–2017, coinciding with the marine heatwave that impacted the ecosystem from 2014–2016, especially in arrowtooth flounder (*Atheresthes stomas*), walleye pollock (*Gadus chalcogrammus*), and Pacific ocean perch (*Sebastes alutus*; Mueter, 2017; Li et al., 2019; Yang et al., 2019). A coincident steep decline in Pacific cod biomass was attributed to increased rates of natural mortality as warmer temperatures during the marine heatwave increased metabolic demands (Barbeaux et al., 2018). In contrast, the distribution and abundance of rockfish (*Sebastes* spp.) appeared independent of temperatures, as this species complex maintained stable biomass trends through the marine heatwave (Cunningham et al., 2018). The stability of abundance may reflect distinctive life history attributes in rockfish, species that are generally long-lived and adapted to environmental change. The stability of the distribution may be reflective of the fact that each species of rockfish occupies a fairly specific depth distribution.

In the Aleutian Islands (PICES region 15), five species assemblages of rockfish (*Sebastes* spp.) were defined based on similarities in their distributions along gradients (Rooper, 2008). Recently, the distribution of adult rougheye rockfish, adult Pacific ocean perch, and shortraker rockfish has been shallower in response to warmer water temperatures. Concurrent increases in overall abundance have been observed for adult rougheye rockfish, shortraker rockfish, northern rockfish, and adult Pacific ocean perch.

On the eastern Bering Sea shelf (PICES region 13), aggregate biomass trends show 6- to 10-year fluctuations with an underlying increase in biomass between 1982–2018 and the highest observed value in 2014. Total catch per unit effort declined after 2014 and dropped sharply in 2017–2018. Over the period 2009–2015, total abundance increased substantially with two highly significant step-increases, one between 2009 and 2010 and another increase between 2013 and 2014. The year 2009 represented a 30-year low because of declines in walleye pollock associated with a series of weak year-classes in 2001–2005. From 2009–2016 the condition (length-weight residuals) of adult walleye pollock and Pacific cod (*Gadus macrocephalus*) decreased, while age-1 pollock condition increased. Evidence suggests varied responses to temperature fluctuations among the groundfish complex, resulting from trait-based climate vulnerability assessments (Spencer et al., 2019).

In the northern Bering Sea (PICES region 14) and southern Chukchi Sea, research has focused on fish assemblages and their association with different water masses. These analyses have identified significant breakpoints between subarctic and arctic groundfish assemblages (Mueter and Litzow, 2008; Stevenson and Lauth, 2012; Baker and Hollowed, 2014). More recent work has examined species-specific responses to water masses and currents in the region (Eisner et al., 2013; De Robertis et al., 2017; Sigler et al., 2017). For example, distribution patterns of salmonids show that previously hypothesized thermal barriers to migrations into the northern Bering Sea are eroding (Moss et al., 2009). Species distribution shifts in cold and warm periods from 2009–2015 suggest that pelagic-oriented species (e.g., walleye pollock, Arctic cod) were constrained by narrow thermal tolerances, whereas demersal species (e.g., Pacific cod, saffron cod) were able to accommodate a wider range of thermal conditions (Baker, 2021).

In the western Bering Sea (PICES region 16) and Okhotsk Sea (PICES region 17), walleye pollock sustain the main commercial fisheries and are an important ecosystem component (Aydin et al., 2002). Contrary to responses in the eastern Bering Sea, warm conditions in the Okhotsk Sea in 2009–2015 resulted in strong year-classes of pollock. Recent efforts to integrate data from the eastern and western Bering Sea (PICES regions 13–16) have provided greater insights into groundfish responses to temperature, connectivity within the Bering Sea, and shifts in distribution across international boundaries (Eisner et al., 2020).

Sharks and tunas

Absence of data is a limitation to informed assessment and fisheries management for oceanic sharks (Camhi et al., 2009). Trend analysis for these species often relies on bycatch and discard statistics (Campana et al., 2009). Regional assessments of shark stocks have also been limited by data quantity and quality, though may be improving (Maxwell et al., 2019). Analyses of oceanic shark species in this timeframe from species-specific catches in the western and central Pacific Ocean from 1995 to 2010 suggest that standardized catch rates of longline fleets declined significantly for blue sharks (*Prionace glauca*) in the North Pacific (5% per year, CI = 2–8%), for mako sharks (*Isurus* spp.) in the North Pacific (7% per year, CI = 3–11%), and for oceanic whitetip sharks (*Carcharhinus longimanus*) in tropical waters (17% per year, CI = 14–20%). Catch rate trends for silky sharks (*Carcharhinus falciformis*) were not significant and most sampled were immature. Both the lack of data and these preliminary findings indicate a need for more directed and ongoing monitoring of these species.

Large pelagic predators such as skipjack tuna (*Katsuwonus pelamis*), albacore tuna (*Thunnus alalunga*), and the blue shark (*Prionace glauca*) are important predators in the lower latitudes and oceanic regions of the North Pacific (PICES regions 23 and 24). While broad ranging, these open water species do respond to climatic variation, local conditions, and oceanic fronts.

Skipjack tuna (*Katsuwonus pelamis*) is one of the widely fished tunas. It inhabits the upper mixed layer (Sund et al., 1981) and is an opportunistic predator, feeding mainly on pelagic fishes and squids. These tunas cover large distances in search of areas with high concentrations of forage fishes (Mugo et al., 2020). In the western North Pacific, these fish migrate north from spring to summer, and south at the onset of

winter, in a seasonal migration pattern. During migration, the fish track highly productive areas associated with physical oceanographic features involving sea surface temperature and ocean color gradients, eddies and streams of warm water entrained into cooler waters (Saitoh et al., 1986; Sugimoto et al., 1992; Mugo et al., 2020). Lagrangian coherent structures (LCSs), or time-evolving surfaces that shape trajectory patterns in complex dynamical systems are apparent over large seascapes. In the California Current albacore tuna exhibit these patterns, which is reflected in the spatial distribution of fishing for albacore tuna, as fishermen track such surface frontal features when targeting tuna (Watson et al., 2018). These species and their movements may offer important insights into larger oceanographic patterns and shifts. Climatic phase shifts may also be important. Central Pacific El Niño events and eastern Pacific El Niño events have been found to have negative effects on skipjack tuna, and relatively higher vulnerability values of the tuna are associated with the simultaneous occurrence of the two types of El Niño events (central Pacific and eastern Pacific El Niño events, Yen et al., 2017).

Tuna are difficult to assess. Skipjack tuna in the western and central Pacific Ocean are considered a single stock for assessment purposes and are not considered overfished (Rice et al., 2014; https://www.fishsource.org/stock_page/1041). According to the 2015 stock assessment, Inter-American Tropical Tuna Commission (IATTC) scientists estimate that the eastern Pacific Ocean stock of skipjack tuna is not overfished and is not subject to overfishing, and remains above target population levels (https://www.fisheries.noaa.gov/species/pacific-skipjack-tuna; https://www.fishsource.org/stock_page/1041). Albacore catch in 2018 decreased by 9% from the 2017 average and 24% from the 2013–2017 average, but the stock is likely not over-fished relative to the limit reference point currently adopted by the Western and Central Pacific Fisheries Commission of 20% Spawning Stock Biomass and the SC10-SA-WP-12 Stock Assessment of Albacore Tuna in the North Pacific Ocean in 2014 (https://wcpfc.int/node/19202).

Salmonids

Salmon production in the North Pacific is at an all-time high (NPAFC, 2018). Increasing temperature, coupled with increasingly extreme variability in environmental conditions year-to-year, have had impacts on stock dynamic and life history patterns (Litzow et al., 2018; Stachura et al., 2013). It appears that physical processes regulating the heat budget of the upper water layer may be the major drivers of Pacific salmon productivity in the North Pacific Ocean. Both the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO) have been empirically linked to changes in the biogeochemistry of the North Pacific Ocean (DiLorenzo et al., 2013), and patterns of North Pacific salmon abundance, productivity, and smolt-to-adult return rates (Mantua, 2015; Ruggerone et al., 2015). Anomalous warming in the Northeast Pacific also appears to have an effect on salmon. Abundance indices in 2014–2015 over-forecast adult returns due to higher than expected mortality in the first summer at sea when juveniles experienced extreme elevated sea temperatures and reduced prey resources in the Gulf of Alaska. The result is that Pacific salmon are increasingly threatened at the southern end of their range (Sydeman et al., 2013), while expanding in the north and into the Arctic. In the high seas, there are no evident shifts in the thermal conditions of salmon habitat. Isotherm positions did not change notably in comparison to the 1970s, with the exception of the area near the North American coastline during the 2014–2016 marine heatwave.

Trends in chum salmon catch anomalies are shown across 5 regions in the North Pacific (Figure 7-2). It appears that trends of several Asian and American salmon stocks are distinct, and important differences in hatchery production are evident. Therefore, each region is analyzed separately in the following sections.

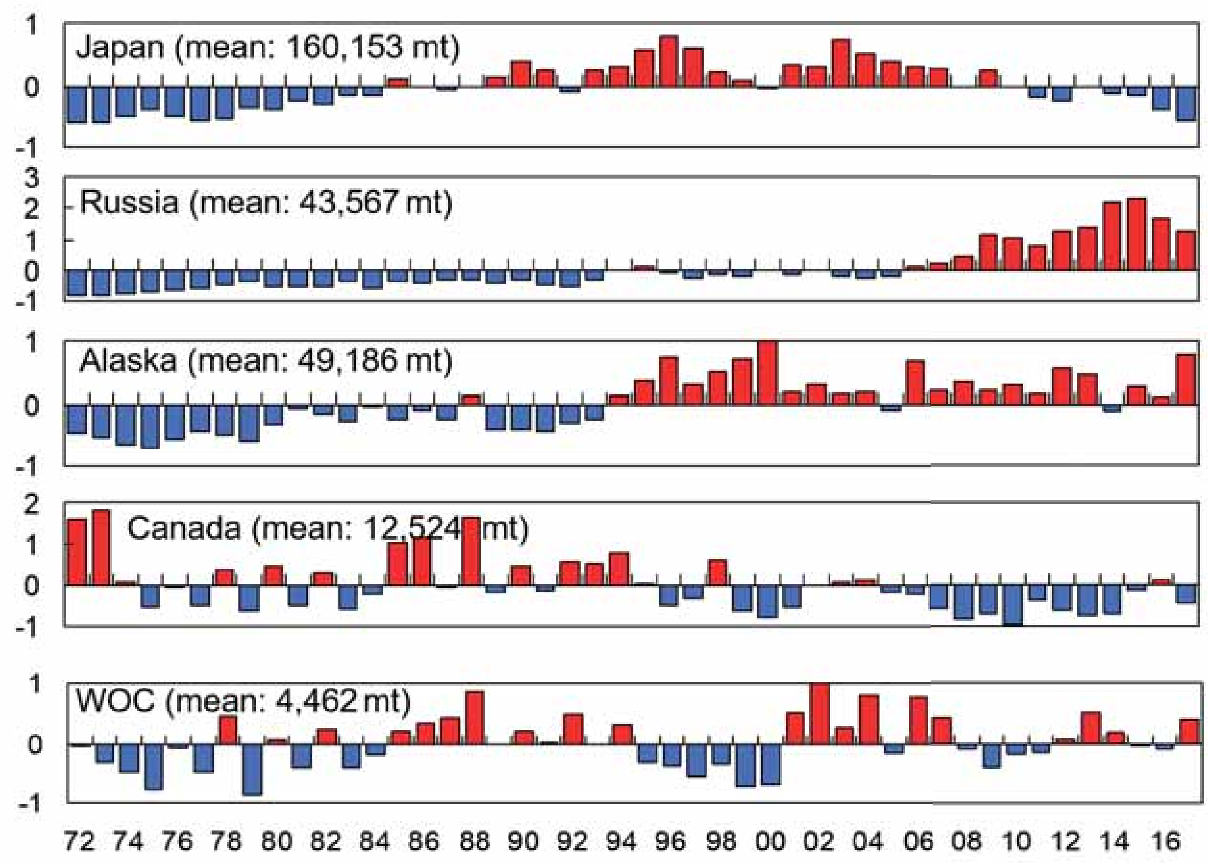

Figure 7-2. Chum salmon catch anomalies by region, 1972–2017 [mass in mt; WOC = Washington, Oregon, and California]. Data from Dr. Shigehiko Urawa, Hokkaido National Fisheries Research Institute, Fisheries Research and Education Agency, Japan.

Western North Pacific

In the western Bering Sea (PICES region 16), there was a substantial increase in Pacific salmon biomass in 2003–2009, which increased further in 2010–2015, reaching a maximum in 2014.

During 2007–2016, the catch of coho in the coastal waters of Japan was 14,000 tonnes, while the annual catch of each of the other four Pacific salmon species was 0–80 tonnes. Sockeye salmon decreased from 2.9 million in 1992 to 0.2 million in 2013–2015 (NPAFC, 2017). The contribution of hatchery fish to total commercial catches is estimated to be 70% for chum salmon, and 20–30% for pink and masu salmon (Morita, 2014). Annual catch of masu increased abruptly from 470 to 820 tonnes during 2007–2011. Masu salmon have been identified as an important predator of chum juveniles. The catch of pink salmon in Japan was predominantly in even-numbered years compared with odd-numbered years during the 1990s and early 2000s. Fluctuations in pink salmon abundance have mirrored climatic changes. Cold ocean winter conditions in 2012–2013 resulted in a decrease in overwinter survival and reduced catch in 2013 and 2014. Warm ocean conditions from the 2015 El Niño were associated with an increase in survival and higher catch of pink salmon in 2016 (Kotenev et al., 2012; Kotenev and Krovnin, 2013; Kaev, 2018).

In the western North Pacific, more than 80% of Asian chum salmon juveniles occupy the Okhotsk Sea (PICES region 17) during their first summer and fall. There is a significant positive relationship between abundance of Japanese hatchery chum salmon juveniles in the Okhotsk Sea and adult returns by brood year (Sato et al., 2018), indicating that year-class strength is determined during the early ocean survival in migration north (Urawa et al., 2018). Low survival of brood year 2012–2014 Japanese chum salmon might be related to cold sea surface temperatures (SST) in spring (early coastal lifestages) and a rapid increase of SST in early summer (Urawa et al., 2018). In the Oyashio Current (PICES region 18),


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chum salmon catches have decreased since 2010 and pink salmon catches decreased during 2011–2015, linked to low SST during juvenile coastal residency and high SST during adult spawning migrations. The abundance of juvenile chum salmon was at high levels (480–553 million fish) in 2012, 2013, and 2015 (Chistyakova and Bugaev, 2016). The abundance of Japanese hatchery-origin juveniles was 120 million fish (survival rate: 6.9%) for the 2010 brood year stock and 240 million (survival rate: 14.9%) for the 2011 brood year stock, but less than 75 million (survival rate: 2.8–4.2%) for the following brood year stocks (2012, 2013, and 2014). Stock abundance and catch of chum salmon increased during the early 2000s in the western Bering Sea, reaching a maximum in 2014.

Sockeye salmon stocks in 2009–2016 along the eastern coast of Kamchatka were relatively high and increased in a linear manner over this time interval. Pink salmon originating from eastern Kamchatka are the primary pink salmon stock in the central Bering Sea (PICES region 15) and central subarctic North Pacific Ocean (PICES regions 23 and 24; Takagi et al., 1981; Myers et al., 1996, 2009). This stock exhibits a strong biennial pattern, with high abundances in odd-years (avg. 106 million pink salmon since 1990) and lower abundances in even-years (avg. 24 million pink salmon). Total abundance of pink salmon around the Pacific Rim reached record abundances (650 million fish) in 2009 and 2011 and comprised approximately 70% of all Pacific salmon. Evidence indicates pink salmon affect zooplankton abundance, which in turn affects phytoplankton abundance (Batten et al., 2018) and may affect growth, age, and survival of other species of salmon (Ruggerone and Connors, 2015; Ruggerone et al., 2016), and diet and reproduction of marine birds (Springer and van Vliet, 2014). There is also growing evidence that pink salmon may have influenced the decline in length-at-age, survival, and abundance of chinook salmon.

Northeast Pacific

North Pacific warming appears to have effects on salmon in the Northeast Pacific. Sockeye salmon in the eastern Bering Sea are spending less time in freshwater and more time in the ocean, leading to larger adults on return but no change in mean age (Ohlberger et al., 2018). Shifts in life history are also evident (Cline et al., 2019). The center of gravity of distributions indicate that juvenile chinook, chum, and pink salmon were farther south in warm years, while juvenile sockeye salmon were distributed farther north and west in warm years (Yasumiishi et al., 2017). Higher abundances of juvenile salmon during recent warm years indicate improved environmental conditions for their survival in the eastern Bering Sea during summer and/or in freshwater rivers and lakes of western Alaska.

Chinook salmon abundance in the Arctic-Yukon-Kuskokwim region of the eastern Bering Sea has been declining since 2007, with no commercial fishing for the species allowed during the 2014 season. The older fish are largely absent, average age is declining, and fish are smaller at age, all trends consistent with size-selective mortality.

Trends in the estimated abundance of juvenile salmon indicate a recent increase in the productivity of Pacific salmon in the eastern Bering Sea. Juvenile sockeye salmon appeared to respond to warming with an expansion in their range and a shift in distribution north leading to an increased presence in the northern Bering Sea (Farley et al., 2020). Juvenile sockeye were the most abundant species followed by pink, chum, and chinook salmon in the eastern Bering Sea and pink and chum in the northern Bering Sea. The 2014 Bristol Bay sockeye salmon run of 41.1 million was 19% above the recent 20-year average (1994–2013) of 34.7 million. In the eastern Bering Sea, both juvenile pink and sockeye salmon had an alternating year pattern with higher abundances in even-numbered years. Juvenile salmon were typically more abundant during warm years (2002–2005 and 2014–2016) than cold years (2007–2013), with the exception of higher juvenile pink and chum salmon abundances during 2007 and 2009.

In the Gulf of Alaska, strong biennial trends in salmon cycles are evident, with high runs in 2013


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and 2015 (Ruggerone and Irvine, 2018). The total number of salmon harvested in 2014 was 44% of the record peak harvest in 2013. Marine survival of Prince William Sound hatchery pink salmon does not appear to have shifted after the 1988/89 or the 1998/99 climate regime shifts. Marine survival was 11.33% in 2013 – an all-time high since 1979. In contrast, Pacific salmon indices in the California Current (PICES region 11) are in decline. Survey catch per unit effort (CPUE, number per km trawled) of both yearling chinook and coho salmon were low and decreasing throughout this time interval. Returns of adult chinook and coho salmon have also been in decline.

Mesopelagic fishes

The total biomass of mesopelagic fish in the North Pacific is uncertain, but these fishes represent an important species group and may constitute the numerically dominant fish assemblage in many regions (Irigoien et al., 2014). Oceanic species occur abundantly on the offshore side of the Kuroshio axis, while pseudo-oceanic species, adapting to certain habitats of continental slopes, slopes of islands, and seamounts occur predominantly on the onshore side (Sassa et al., 2004; Ohshimo et al., 2012; Sassa and Konishi, 2015). While there is substantial interannual variability and decadal-scale trends (Watanabe and Kawaguchi, 2003), myctophids and mesopelagic species showed an increasing trend in abundance after 2000, possibly related to the increasing trend in water temperature in the Kuroshio region (PICES region 22; Wu et al., 2012).

Squids

In the western Pacific (PICES region 22), Japanese common squid (*Todarodes pacificus*), have experienced relatively high abundance for several decades. However, they are now declining as part of an apparent regime shift in the pelagic community (Takasuka et al., 2008b;Takasuka, 2018). In the Oyashio Current region (PICES region 18), there has been considerable variation in landings (Kawabata et al., 2006). In the western Bering Sea (PICES region 16), there was a substantial increase in Boreopacific armhook squid (*Boreoteuthis borealis*) biomass in 2003–2009. In the California Current, market squid (*Doryteuthis opalescens*) and krill (euphausiids) were at fairly high abundance levels in most areas (Ralston et al., 2018). Potential habitat for neon flying squid (*Ommastrephes bartramii*) appears to fluctuate in response to phase shifts in the PDO. During a cold to warm PDO shift, decreases were noted in the summer distributions of *O. bartramii* (Alabia et al., 2020). Compared to El Niño events, La Niña events and normal climate conditions led to increased habitat and a shift north in the latitudinal center of gravity for this species (Yu et al., 2019). Both mature and immature squids (*Boreotheuthis borealis*, *Gonatus kamschaticus*, *Engraulis japonicus*, *Todarodes pacificus*, *Onychoteuthis borealijaponica*) are transported from the North Pacific Ocean to the Bering Sea, with high abundances during early life stages in the western Bering Sea and Aleutian Islands (Glebov et al., 2010).

Jellyfish

Jellyfish in the western Bering Sea and Aleutian Islands decreased more than 6-fold between 2003–2009 (800 kg km^{-2}) and 2010–2015 (125 kg km^{-2}). Pyrosomes, salps and other colonial pelagic organisms were also noted in high abundance in the California Current and Gulf of Alaska in 2014–2015, during the marine heatwave (Brodeur et al., 2008, 2018; Palsson et al., 2017; Ruzicka et al., 2020).


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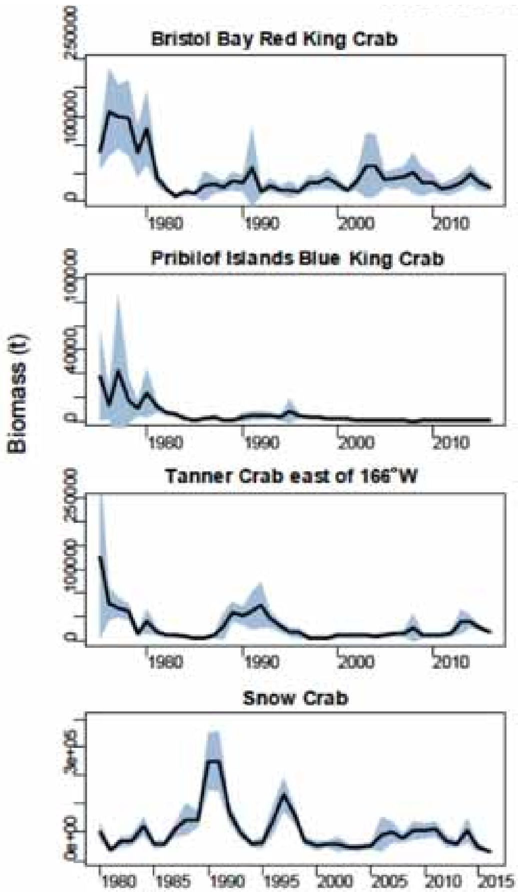

Figure 7-3. Trends in estimated biomass of 7 stocks (4 species) of commercially important crabs (mature males) in the Alaska waters in the time period of interest, as part of a time series initiated in 1975.

Crabs

Historical trends of commercial crab biomass and abundance are highly variable (Figure 7- 3) but there has been a general decrease in biomass and abundance in red king, blue king, and Tanner crab stocks in the Eastern Bering Sea since 2014 (Richar and Zacher, 2019). In the northern Bering Sea, St. Matthew blue king crab continued declines to the lowest levels observed for this stock (Zheng and Ianelli, 2018). Most declines are in the eastern stocks while western stocks have been increasing or have been stable in recent years. In the Yellow Sea (PICES region 20), species composition of annual commercial crab catch suggests the fish and invertebrate community structure has changed sequentially with a distinct (1999–2014) period, matching reported regime shifts in the North Pacific by past studies (Hare and Mantua, 2000; Zhang et al., 2000; Katoh et al., 2006; Hwang and Jung, 2012). In the same time period, the biomass of flower crabs (*Portunus pelagicus*) and blue crab (*Portunus trituberculatus*) increased in contrast to depressed populations of flatfish benthivores (Sea Around Us, 2017).

Among commercial crabs in the Okhotsk Sea (PICES region 17), the most abundant species in the last decade have been snow crabs (*Chionoecetes opilio*, *Chionoecetes bairdi*) and red king (*Paralithodes camtschaticus*), golden king (*Lithodes aequispinus),* and blue king *(Paralithodes platypus*) crabs. Snow crabs were present in the northern Okhotsk Sea shelf. Red king crab stocks in Kamchatka were overfished and harvesting was banned from 2009 to 2012, which appears to have had a positive effect on the population. Pribilof Islands (within PICES region 13) crab stocks remain extremely depressed, possibly due to negative trends in benthic production or a negative benthic response to environmental variability (Richar and Zacher, 2019). Pelagic red crabs (*Pleuroncodes planipes*) in the California Current appear to be increasing since 2015.

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[8] Highlights

- Warm water events in the Northeast Pacific, particularly during the 2014–2016 marine heatwave, were associated with poor reproduction and widespread mortality events of marine birds and mammals.
- There were also localized reproductive failures in the Western North Pacific, but owing to a lack of wide-spread data, no large-scale coherent patterns were evident.

Lori Waters

D.Irons

Chapter 8: Marine Birds and Mammals

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Introduction

The North Pacific is home to a diverse group of marine bird and mammal species. Many are endemic within this range, though some regularly migrate outside the region, such as Arctic terns *Sterna paradisaea* (which migrate to the Southern Ocean) and bowhead whales *Balaena mysticetus* (which migrate to the Arctic Ocean). Marine birds and mammals spend most of their time at sea, foraging primarily on fish and invertebrates (e.g., squids and zooplankton). Most marine bird breeding colonies or pinniped (e.g., seals, sea lions, walruses) rookeries are located on land although there are some exceptions, such as ice platforms for some seal species and kelp beds for sea otters. During the breeding season, marine birds and pinnipeds are "central place foragers", meaning that their foraging is restricted to a limited distance from the breeding site that allows them to return to feed their young. While cetaceans (e.g., whales, dolphins, porpoises) may have discrete calving areas, the young typically travel with their mothers, and thus parents are not restricted to central place foraging.

Marine birds can be grouped by trophic ecology to those that primarily feed on fish (piscivorous) or zooplankton (planktivorous), though for many species, such as thick-billed murres *Uria lomvia*, the relative proportion of fish or plankton in their diets varies by life stage and season (Gaston and Hipfner, 2000). Marine birds can also be grouped by whether they are primarily surface or near-surface foragers (e.g., kittiwakes *Rissa* spp.) or divers (e.g., puffins *Fratercula* spp.). Like marine birds, marine mammal diets vary in relation to ontogeny and foraging strategies. For this synthesis, we focus on pinnipeds (piscivorous) and large baleen whales (planktivorous and piscivorous), although additional marine mammal species were included in PICES regional reports (Table 8-1).


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Table 8-1. Diet-type grouping of marine bird and mammal species in PICES regions.

Marine birds - Alcids	**PICES region**	**Procellarids**	**PICES region**
plank Cassin's auklets	11	inverts Black footed albatross	11
plank Crested auklets	14, 15	pisc Pink-footed shearwater	11
plank Least auklets	14, 15	mixed Sooty shearwater	11
plank Whiskered auklet	15	pisc Streaked Shearwater	20
mixed Rhinoceros auklet	18	mixed Fork tailed storm petrels	12, 15
mixed Ancient murrelets	11, 15	mixed Leach’s storm petrels	12, 15
pisc marbled murrelets	11	mixed Swinhoe’s storm petrels	20
pisc Scripps's murrelets	11	**Seabirds - Gulls**	
pisc Common murre	12, 15, 18	pisc Elegant tern	11
mixed Thick billed murre	14, 15	pisc Sabine’s gull	11
pisc Tufted puffins	12, 15, 18	mixed Glaucous-winged gull	15
pisc Horned puffins	15	mixed Black-tailed gull	18, 20
pisc Pigeon guillemot	15	mixed Slaty-backed gull	18
Spectacled guillemot	18	mixed Saunders gull	20
Marine birds - Cormorants		pisc Black-legged Kittiwake	12, 15
pisc Double crested cormorant	15	mixed Red-legged Kittiwake	15
pisc Red faced cormorant	15		
pisc Pelagic cormorant	15		
pisc Japanese Cormorant	18		
Marine Mammals - Pinnipeds		**Marine Mammals - Baleen Whales**	
Steller sea lions	12, 15, 18	Fin	12
Spotted seals	18, 20	Gray	12
Harbor seals	15, 18	Sei, Minke, Bryde’s	23
California sea lions	11	Humpback	11, 14
Northern fur seals	13	Bowhead	14

pisc = piscivorous, plank = planktivorous, mixed = both

Marine bird populations and productivity

Large-scale changes in North Pacific marine bird populations are not well known within the focal period of 2009–2016. For some species, there has been recovery from historic hunting or egging, such as with short-tailed albatross *Phoebastria albatrus* in Japan (Zador et al., 2008) or common murres *Uria aalge* in central California (Ainley and Lewis, 1974). At the international level, 12 marine bird species in the North Pacific are of current conservation concern, although local conservation status can vary among and within PICES regions. (Table 8-2). There are also examples of range expansions (movement north) that may be related to ocean climate change (e.g., the elegant tern *Thalasseus elegans* has extended its breeding range northward in California (PICES region 11; Velarde et al., 2015). Current major population threats at nesting colonies are habitat loss (including rising sea levels, storms, and degradation), introduced plants and animals, and introduced predators. There also continues to be localized subsistence hunting and egging, such as with murres in the Bering Sea (Naves, 2015), which may pose a limited threat. At sea threats include fisheries interactions (bycatch), but primarily food supply limitations, which seem to be increasingly related to changes in climate (Gibble, et al., 2018, Jones, et al., 2018).

In contrast with marine mammals, there are numerous datasets of marine bird productivity (i.e., the number of young produced per female per year) for many locations across the North Pacific. In general, breeding success exhibited high variability during the 2009–2016 focal period. Many breeding failures occurred from 2014–2016 across the North Pacific. This poor productivity was related to reduced food resources associated with the development and persistence of the 2014–2016 Northeast Pacific marine heatwave (Bond et al., 2015; Yang et al., 2018).

Large-scale marine bird die-offs occurred during the focal period (e.g., Cassin's auklets *Ptychoramphus aleuticus* during winter 2014/2015 (Jones et al., 2018), and Gulf of Alaska common murres during winter 2015/2016 (Piatt et al., 2020)). Mortalities have been substantial, with 100,000s affected. In almost all cases, starvation has been implicated, demonstrating extreme food shortages. Because marine birds are long-lived species, adult mortality has larger population impacts than reproductive failures; we anticipate population-level impacts will be observed over time from these events.

Matt Baker

Matt Baker

Pinniped populations and productivity

Population trends for pinnipeds show substantial regional variation. For example, during the 2009–2016 focal period, population growth of Steller sea lions shows a strong geographical gradient, with a general pattern of increasing at the eastern and western range ends contrasting with declines in the center of their range (western Aleutian Islands, PICES region 15). Numbers are increasing and are near or at carrying capacity in the eastern Gulf of Alaska (PICES region 12) and increasing in the western Pacific (PICES regions 17 and 18) the Kuril Islands, Sakhalin, and northern Okhotsk Sea. A notable "superabundance" was recorded in Cape Soya (Hokkaido Island) in May 2016. In the central North Pacific, colony size is stable in the central Aleutians, and Kamchatka (PICES region 16), but is declining in the western Aleutians. Competition with fisheries remains a threat to recovery, along with environmental change, killer whale predation, and pollution.

The eastern Pacific stock of northern fur seals has experienced a long period of decline due to hunting, and declines continued at some rookeries between 2009 and 2015. For example, at St. Paul Island, Pribilof Islands, in the eastern Bering Sea (PICES region 13), the largest northern fur seal rookery continues a long-term decline in numbers, with poor pup production. The rookeries at St. George Island, Pribilof Islands, are stable, and those on Bogoslof Island have increased dramatically. The increase at Bogoslof Island, however, has not been enough to offset the decreasing numbers in St. Paul Island which drives the overall trend of the eastern Pacific stock.

Interactions with fisheries are increasing along with some populations. Increasing numbers of Steller sea lions near Hokkaido (PICES region 18) are impacting coastal fisheries, damaging fishing nets and feeding off the nets, and thus culling has been implemented. Similar impacts of increasing spotted and harbor seals around Hokkaido have had detrimental effects on the salmon set net fishery, which has prompted an annual cull to protect fisheries.

Cetacean populations

Populations of large cetaceans are generally on the rise, recovering from exploitation which ended in the early 1970s. However, one survey in the western North Pacific (PICES region 23), recorded decreasing numbers of Sei, Bryde's, and Minke whales. Also, Arctic whale species seem to have decreased presence or are migrating north earlier from the area around Bering Strait. During the focal period, subarctic species such as humpback, fin and killer whales expanded into the northern Bering Sea and Chukchi Sea (PICES regions 13 and 14, respectively), with more frequent sightings over longer periods each year. For example, humpback whales are increasing in the California Current area (PICES region 11), and have possibly reached carrying capacity in Southeast Alaska (PICES region 12), and expanded northward into the Arctic. The overall recovery of whales is still partial, and several remain listed as endangered by the International Union for the Conservation of Nature (IUCN; Table 8-2).

Recovered or recovering large cetacean populations may be exerting top down control on local food webs, making the systems potentially less predictable. This top down control may also impact fisheries, especially fisheries for small pelagic species, though these impacts are not widely accepted and may be related to climate as well. For example, Sei whale diets typically included Japanese anchovy in the 2000s, but it changed noticeably to mackerel and sardine in 2014 and 2015. The substantial seasonal consumption of anchovy by Sei, Minke and Bryde's whales suggests it should be incorporated in stock assessments.

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Miguel Neves

Recovery trends are tempered by concerns regarding the health of other marine mammal populations. For example, in Glacier Bay, Gulf of Alaska (PICES region 12), the number of calves in a well-documented summer population of humpback whales had been generally increasing until 2010, mirroring the overall population recovery to apparent carrying capacity. However, the number of calves declined abruptly in 2015 and has remained low since then (Gabriele and Neilson, 2018). Poor foraging conditions resulting from the 2014–2016 marine heatwave have been linked with the abrupt reduction in humpback whale reproductive output. The heatwave has also been linked to an unusual mortality event from 2015 to 2016 in the Gulf of Alaska, comprising multiple species of large baleen whales. Similarly, there was a large die-off of California sea lions in the California Current area between 2013 and 2016.


Lori Waters


Lori Waters

Table 8-2. IUCN redlist of marine birds and mammals of the PICES regions of the North Pacific (IUCN 2019, www.iucnredlist.org). Any changes in status relative to that documented in NPESR2 (IUCN 2009) are noted. Note that protected status of a species may vary between countries. IUCN categories: NT Near Threatened, VU Vulnerable, EN Endangered and CR Critically Endangered.

English name	Latin name	Status 2009	Status 2019	As of	Trend	PICES region
Marine birds						
Short-tailed albatross	*Phoebastria albatrus*	VU	VU	07.08.18	↑	23, 24, Oceanic North Pacific
Laysan albatross	*P. immutabilis*	VU	NT	07.08.18	—	23, 24, Oceanic North Pacific
Black-footed albatross	*P. nigripes*	EN	NT	07.08.18	↑	Oceanic Pacific, including 23, 24, 25
Ashy storm-petrel	*Hydrobates homochroa*	EN	EN	07.08.18	↓	11, California Current System
Long-billed murrelet	*Brachyramphus perdix*	NT	NT	10.08.18	↓	17, Okhotsk Sea
Kittlitz's murrelet	*B. brevirostris*	CR	NT	07.08.18	↓	12–18, Alaska to Okhotsk Sea
Marbled murrelet	*B. marmoratus*	EN	EN	07.08.18	↓	12–15, Gulf of Alaska, Aleutians
Craveri's murrelet	*Synthliboramphus craveri*	VU	VU	07.08.18	↓	11, S. California Current
Guadalupe murrelet	*S. hypoleucus*	*	EN	07.08.18	↓	11, S. California Current
Scripp's murrelet	*S. scrippsi*	*	VU	07.08.18	↓	11, S. California Current
Japanese murrelet	*S. wumizusume*	VU	VU	07.08.18	↓	18, 22, Kuroshio and Oyashio
Steller's eider	*Polysticta stelleri*	VU	VU	07.08.18	↓	Bering Sea, Arctic Ocean, including 13, 14, 16
Marine mammals						
Steller sea lion	*Eumetopias jubatus*	EN	NT	04.02.16	↑	11–18, Coastal North Pacific
Sei whale	*Balaenoptera borealis*	EN	EN	25.06.18	↑	World oceans
Blue whale	*B. musculus*	EN	EN	16.03.18	↑	World oceans
Fin whale	*B. physalus*	EN	VU	04.02.18	↑	World oceans
North Pacific right whale	*Eubalaena japonica*	EN	EN	19.12.17	?	11–24, Northern North Pacific, Bering Sea
North Pacific right whale	*E. japonica*	CR	CR	18.12.17	?	Northeast Pacific subpopulation
Bowhead whale	*Balaena mysticetus*	EN	EN	07.03.18	↓	Okhotsk Sea subpopulation
Grey whale	*Eschrichtius robustus*	CR	EN	01.01.18	↑	Western North Pacific subpopulation
Beluga whale	*Delphinapterus leucas*	CR	CR	22.06.17	↓	Cook Inlet, Gulf of Alaska

*Previously listed together as S. *hypoleucus* assessed separately 2014

International Union for the Conservation of Nature (IUCN) Red List Category Meanings

Extinct (EX): no reasonable doubt that the last individual has died.

Extinct in the Wild (EW): known only to survive in captivity, cultivation or well outside its natural range.

Critically Endangered (CW): facing extremely high risk of extinction in the wild.

Endangered (EN): facing a very high risk of extinction in the wild.

Vulnerable (VU): facing a high risk of extinction in the wild.

Near Threatened (NT): close to qualifying, or likely to qualify for a threatened category in the near future.

Least Concern (LC): population is stable enough that it is unlikely to face extinction in the near future.

Data Deficient (DD): not enough information on abundance or distribution to estimate its risk of extinction.

John Ford

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Breakout Box

Marine pollution in the North Pacific Ocean

Author: Juan José Alava

Pollution can adversely affect the health and abundance of marine biota, especially in densely-populated coastal areas. The downstream socio-economic consequences can be significant, with numerous examples of consumption advisories, commercial fishery closures, commercial trade interdictions and diminished aboriginal access to food resources around the North Pacific Ocean. PICES Working Group on Emerging Topics in Marine Pollution (WG 31) convened a scientific session at PICES-2015 in Qingdao, China, from which a special issue on indicators of marine pollution in the North Pacific Ocean was published (Brown et al., 2017).

Anthropogenic pollutants, including persistent organic pollutants (POPs), metals, antifouling biocides, and marine debris/ocean plastics are found throughout the North Pacific (Wilkening et al., 2000). Atmospheric transport of POPs delivers these contaminants from temperate, subtropical and tropical areas to oceanic and coastal regions of the North Pacific (Iwata et al., 1993, 1994; Wania and Mackay, 1996; Wania and Dugani, 2003; Gouin et al., 2004).

Persistent organic pollutants

There are two general categories of POPs: the legacy compounds including polychlorinated biphenyls (PCBs), dichloro-diphenyl-trichloroethanes (DDTs) and hexachlorocyclohexanes (HCHs), as well as emerging POPs such as polybrominated diphenyl ethers (PBDEs) and perfluorinated chemicals (PFCs). All are persistent, bioaccumulative and toxic. Some POPs, including PCBs and DDTs, were banned in developed and industrialized countries during the 1970s. However, organochlorine pesticides (OCPs) are still used and, along with emerging POPs such as PBDE flame retardants and PFCs, continue to contaminate food webs.

POPs are still found in relatively high concentrations in the apex predators (marine mammals and marine birds) of the North Pacific. There are indications of declining concentrations in sentinel species (i.e., harbour seals), as illustrated in Figure 1.

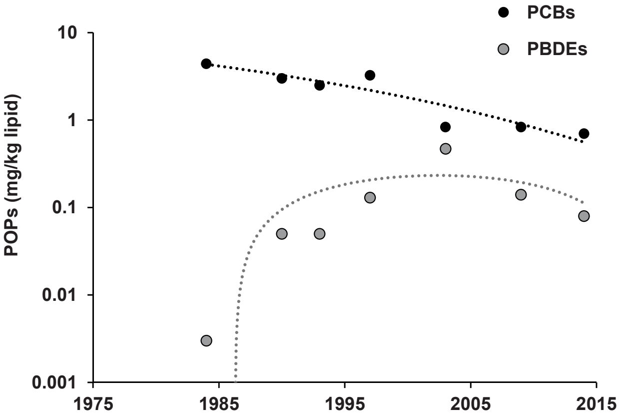
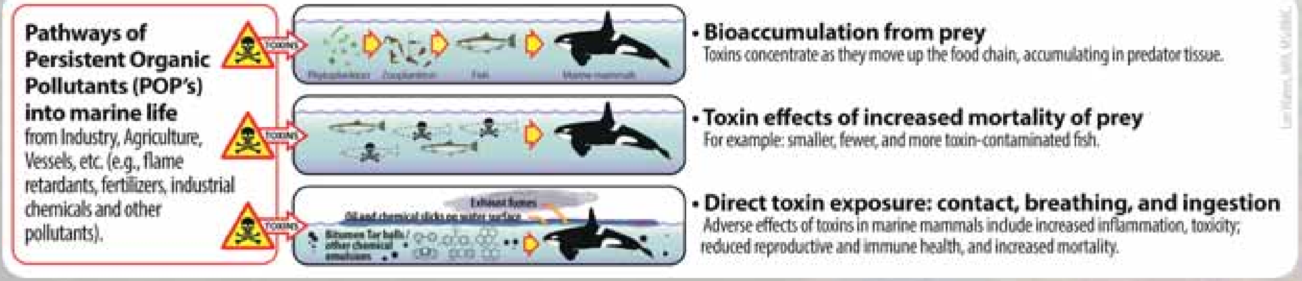


Figure 1. Estimated temporal trends in PCB and PBDE concentrations (log scale in mg/kg lipid) in harbour seals from the Strait of Georgia (BC, Canada), based on the trends observed in harbour seals from Puget Sound, WA, USA (Ross et al., 2013). From Alava et al., (2019). Report of Working Group 31 on Emerging Topics in Marine Pollution. PICES Sci. Rep. No. 56.

Mercury

Mercury is emitted from both natural and anthropogenic sources, is highly toxic, and can bioaccumulate in marine ecosystems, especially organic forms such as methylmercury (CH_3Hg^+). Anthropogenic sources are dominated by small-scale gold mining operations (37%) and coal-fired power plants (24%) which contaminate remote oceanic regions and marine biota, including economically important fisheries (UNEP, 2013; Lamborg et al., 2014). Anthropogenic emissions and releases have doubled the amount of mercury in the top 100 meters of the world's oceans in the last 100 years (UNEP, 2013). The North Pacific is one of the major sinks for mercury emissions, and methylmercury bioaccumulation in apex predators has been documented in sentinel species from the northeastern Pacific (Peterson et al., 2015; Noël et al., 2016). Mercury has been detected in sediments from Korea, Russia and Canada, raising concerns about chronic contamination of the marine environment and metal pollution risk for seafoods in these countries.



Pathways of Persistent Organic Pollutants (POP's) into marine life from Industry, Agriculture, Vessels, etc. (e.g., flame retardants, fertilizers, industrial chemicals and other pollutants).

- **Bioaccumulation from prey**
  Toxins concentrate as they move up the food chain, accumulating in predator tissue.
- **Toxin effects of increased mortality of prey**
  For example: smaller, fewer, and more toxin-contaminated fish.
- **Direct toxin exposure: contact, breathing, and ingestion**
  Adverse effects of toxins in marine mammals include increased inflammation, toxicity; reduced reproductive and immune health, and increased mortality.

Hydrocarbons and oil spills

The pollutants of greatest concern from oil spills include volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) (Ross and Desforges, 2014). While acute catastrophic oil spills are among the more obvious sources of chemical pollution at sea and along fragile coastal areas, chronic spills of hydrocarbons from multiple sources (such as runoff from impervious surfaces on urbanized areas and parking lots, small boats, fishing vessels, marinas and fuel stations) represent an ongoing and largely uncharacterized threat for marine mammals (Harris et al., 2011). For example, the volume of used motor oil spilled annually into Canadian waters is equivalent to seven times the amount released by the Exxon Valdez tanker in 1989 (de Villiers, 1999).

Antifouling compounds

Organometallic biocides, including tributyltin (TBT) and other organotin (OT) compounds, are used mainly as antifouling paints on ship hulls and readily bioaccumulate in marine mammals and humans (Linley-Adams, 1999; Tanabe, 1999; Antizar-Ladislao, 2008). TBT compounds have been associated with immunotoxicity and hepatotoxicity in sea otters, bottlenose dolphins and Dall's porpoises (Kannan et al., 1997, 1998; Nakata et al., 2002; Murata et al., 2008). Regulatory bans of TBT compounds in several North Pacific countries, including Korea, Japan and Canada, have resulted in new organotin-free substitutes being used that have already been found in the coastal marine environments of Korea and Japan since the banning of TBTs.

Ocean plastics

Plastics in the ocean are a major threat to marine life and ecosystems as plastic marine debris can lead to entanglement and ingestion, leach toxic chemicals, and provide vectors for POPs and invasive species. Of particular concern are microplastics (particles less than 5 mm), which are manufactured both as plastic resin pellets and generated as larger plastic items breakdown into smaller particles (Moore, 2008; GESAMP, 2010). Most plastics are derived from land-based sources, including household and industrial wastewater, aquaculture, shipping and tourism.

In situ observations as well as global microplastic transportation models have shown higher microplastic abundance in the North Pacific and its marginal seas than in other oceans (Desforges et al., 2015; Lusher, 2015; Van Seville et al., 2015; Lebreton et al., 2018). Microplastics are increasingly recognized as a potential threat to biota in the ocean; with decreasing size they become more bioavailable to small aquatic organisms and the chemicals in microplastics are transferred to an organism upon ingestion. Microplastics represent trans-boundary pollution which can also deliver associated chemicals and invasive organisms to regions far removed from source.


Ed Lyman

David Shea

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[9]

Highlights

- From 2000 to 2017 economic growth rates in PICES member countries exceeded the global mean; population growth rates were below the global mean.
- Since 2000 the catch by PICES member countries of diadromous fish, marine fish, and crustaceans have increased slightly, while there has been a steady decline in the catch of molluscs.
- There have been substantial increases in aquaculture production of freshwater fish, diadromous fish, marine fish, crustaceans, molluscs, and aquatic plants by all PICES member countries, with China leading the way.
- Per capita annual seafood consumption increased across PICES as a whole, with decreases in per capita annual consumption of pelagic, demersal, and other marine fish being offset by increases in per capita consumption of freshwater fish, crustaceans, molluscs, and aquatic plants overall (although increases and decreases varied by country).

Tom Giognso

Chapter 9: Human Dimensions

Author: Keith R. Criddle

Introduction

The status and trends of human dimensions of the North Pacific Ocean are influenced by changes in the distribution and abundance of fish and invertebrate populations, the occurrence of natural disasters, changes in regional and global economies, changes in human populations and demography, and changes in the demand for seafood. The North Pacific is among the most important fishery regions in the world, and PICES' six member countries are world leaders in freshwater and marine fisheries and aquaculture. Wild fisheries are important to the PICES member countries, with catches from the North Pacific representing 44% of their production of crustaceans, 42% of their production of fish, and 16% of their production of molluscs (Criddle, 2020). Between 2000 and 2017, the average catch from the North Pacific represented 23.4% of the global catch of fish, and yielded 41% and 35% of the global catches of crustaceans and molluscs, respectively. Aquaculture and wild fisheries production of PICES' six member countries produced 37% of the global supply of fish, and 52% and 75% of the global supply of crustaceans and molluscs, respectively. (Criddle, 2020).

In 2000, the human population of PICES' member countries totaled 1.9 billion people – 31.3% of the global population (United Nations Basic Statistics, 2020). By 2017, it exceeded 2.1 billion people, but only represented 28% of the global population. That is, population growth in PICES member countries did not keep pace with global population growth. Within PICES, population growth varied from a statistically significant increase of 7.7 million people per year in China to a slight but statistically insignificant decrease in Russia (–19.5 thousand people per year). By itself, China accounts for 67.3% of the population of the PICES member countries. From 2000 to 2017, Canada experienced the largest average annual percent population increase (1.1%), but this was substantially below the average annual rate of increase for the combined non-PICES (Rest-of-World, ROW) nations (1.43%).

PICES includes the world's three largest economies (USA, China, and Japan); Canada, Korea, and Russia are also among the top 12 global economies (United Nations Basic Statistics, 2020). Together, PICES' six member countries generated $23.2 trillion in gross domestic product (GDP) – 48.2% of the global economy in 2000; in 2017, the GDP of PICES member countries was US$40.6 trillion, 51.1% of global economic activity. So although PICES encompasses a declining fraction of the global population, it encompasses an increasing fraction of the global economy.

In addition to the human dimensions associated with seafood production, there are important human dimensions to the consumption of seafood. It is generally expected that consumer demand for seafood will be positively correlated with income. While per capita GDP is not equivalent to income, changes in income are generally assumed to be positively correlated with changes in per capita GDP. Thus, because per capita GDP in most PICES member countries exceeds the global average, it might be anticipated that the demand for seafood in these countries might also exceed the global average. However, there are striking cultural differences in food preferences, particularly for aquatic products.

A summary of trends in wild fisheries of the North Pacific, and the production of aquatic products by and within PICES member countries are presented below.

Wild fisheries

Annual observations (2000–2017) of the total catch of fish, crustaceans, and molluscs from the North Pacific are shown in Figure 9-1. The annual mean (2000–2017) total catch of all fish (with sub-groups diadromous fish and marine fish), crustaceans, and molluscs, and take of marine mammals from the North Pacific are reported in Table 9-1. Overall trends include slight increases for catches of crustaceans (7,992 mt/year), diadromous fish (9,342 mt/year), and marine fish (126,012 mt/year). However, the

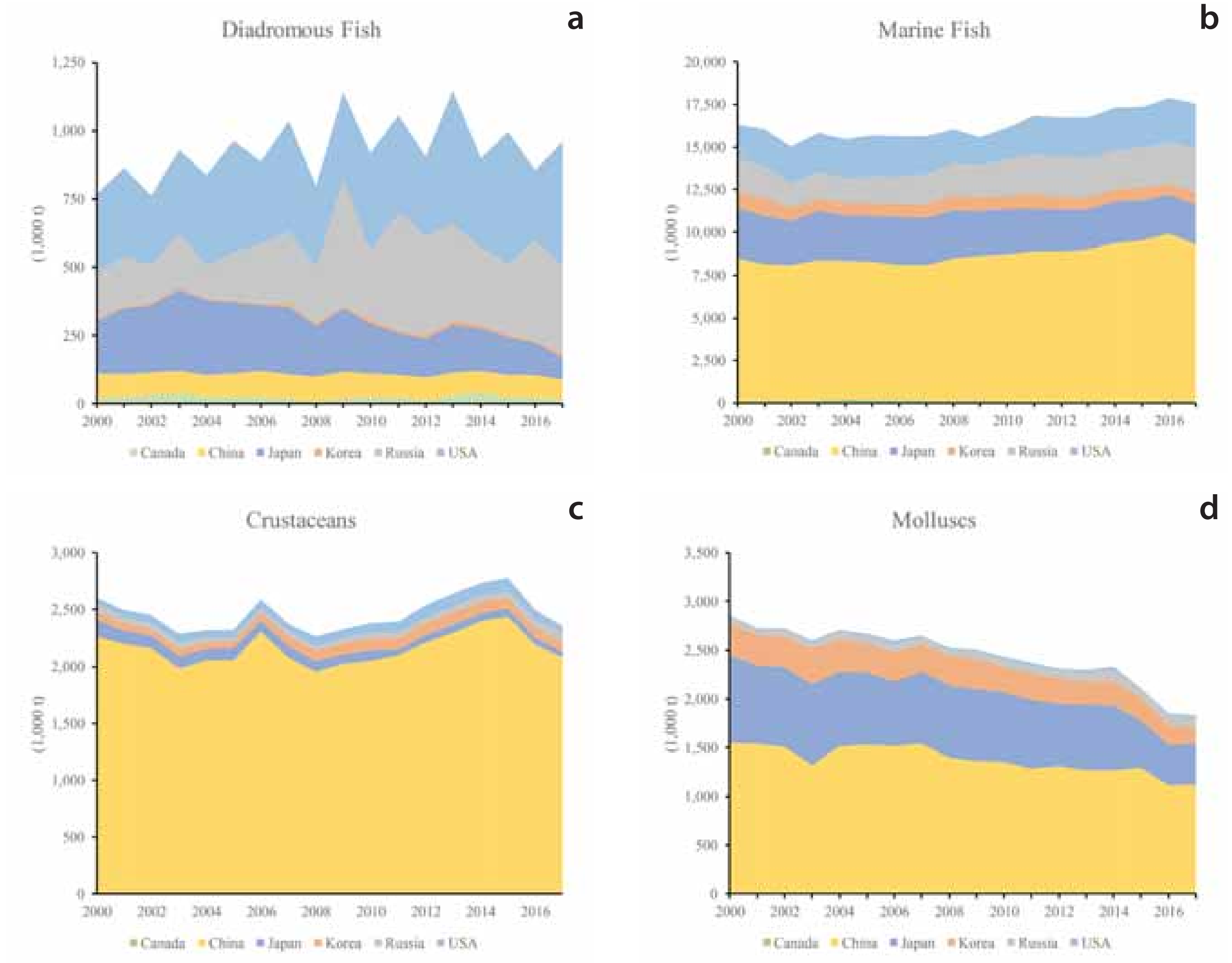

Figure 9-1. Annual catch (1000 mt) of: a) diadromous fish, b) marine fish, c) crustaceans, and d) molluscs from the North Pacific, 2000–2017. Source: UN FAO Fish Stats (2020).

increases in crustaceans and diadromous fish are not statistically significant (Table 9-2). The total catch of molluscs from the North Pacific has declined by a statistically significant average of 52,190 mt/year over this 18-year (2000–2017) period (Table 9-2).

From 2000 to 2017, over 87% of the annual mean North Pacific catch of diadromous fish (primarily Pacific salmon) was harvested by three member countries: the USA (37.4% of total), Russia (28.6% of total), and Japan (21.3% of total; see Table 9-1 and Figure 9-1a). During these 18 years, there has been a statistically significant decline (–0.64% per year) in the share of diadromous fish caught by Japanese fishers and a statistically significant increase (4.87% per year) in the share of diadromous fish caught by Russian fishers (Table 9-2). The shares of North Pacific diadromous fish caught by Canada and China have declined, but the declines are not statistically significant (Table 9-2). The shares of North Pacific diadromous fish caught by the USA and Korea have increased; the increase in Korean catches is statistically significant, but small; the increase in USA catches is not statistically significant (Table 9-2).

On average, catches by China between 2000 and 2017 accounted for over 50% of all catches of marine fish from the North Pacific (Table 9-1, Figure 9-1b). China's share of marine fish catch has increased at an average (statistically significant) rate of slightly more than 1% per year (Table 9-2). Together, Japan, the USA, and Russia harvest a little over 40% of all marine fish from the North Pacific (Table 9-1, Figure 1b). From 2000 to 2017, the shares of the North Pacific

Table 9-1. Annual mean (2000–2017) total catch of fish (mt), crustaceans (mt), and molluscs (mt), and take of marine mammals (number) from the North Pacific by PICES member countries and all other countries (Rest-of-World, ROW). Source: UN FAO Fish Stats (2020).

	Diadromous fish	Marine fish	All fish	Crustaceans	Molluscs	Marine mammals
Canada	23,347	140,416	163,763	7,445	3,431	1
China	85,938	8,571,002	8,656,940	2,149,969	1,375,627	-
Japan	197,952	2,594,734	2,792,686	88,318	689,611	-
Korea	8,929	776,378	785,306	83,574	280,255	-
Russia	265,514	1,987,618	2,253,132	52,571	82,966	6,908
USA	347,143	2,261,858	2,609,001	81,277	17,158	1,077
PICES nations	928,823	16,332,006	17,260,828	2,463,154	2,449,048	7,986
Non-PICES nations	86	706,959	707,045	46,293	31,213	-
Total	928,909	17,038,965	17,967,873	2,509,447	2,480,261	7,986

Table 9-2. Mean annual percent change (%) (2000–2017) in the catch (mt) or take (number) from the North Pacific by PICES member countries and all other countries (ROW). Derived from UN FAO Fish Stats (2020).

	Diadromous fish (%)	Marine fish (%)	All fish (%)	Crustaceans (%)	Molluscs (%)	Marine mammals (%)
Canada	-1.22	-1.48	-1.44	-1.95	-5.08*	11.89
China	-0.41	1.06*	1.04*	0.35	-1.70*	-
Japan	-4.64*	-1.30*	-1.54*	-4.78*	-3.14*	-
Korea	3.57*	-1.36*	-1.30*	2.53*	-2.93*	-
Russia	4.87*	3.02*	3.24*	2.27	2.29*	-5.88*
USA	1.70	0.89	1.00*	2.68*	2.84	-16.86*
PICES nations	1.01	0.76*	0.78*	0.35	-2.08*	-7.36*
Non-PICES nations	-4.10	0.22	0.22	-1.59	-3.74	-
Total	1.01	0.74*	0.75*	0.32	-2.10*	-7.36*

* denotes values that are statistically significant at a 5% level.

marine fish catches taken by Japan and Korea have experienced statistically significant declines; Canada's share has declined at a faster rate, but because Canada's share has been highly variable, the decline is not statistically significant (Table 9-2). The share of the North Pacific marine fish caught by Russia has increased at an average (statistically significant) rate of over 3% per year during this period (Table 9-2). The share of North Pacific marine fish catch by the USA has increased over this period, but the increase is not statistically significant (Table 9-2).

China harvests almost 86% of all crustacean harvests from the North Pacific, a share that has increased slightly over the past 18 years (Table 9-1, Figure 9-1c). Japan's share of the North Pacific crustacean catch has declined by almost 5% per year (Table 9-2). North Pacific catches of crustaceans by Korea, Russia, and the USA have all increased at statistically significant rates over the past 18 years (Table 9-2).

China, Japan, and Korea account for over 95% of the North Pacific mollusc catch (Table 9-1, Figure 9-1d). Over the past 18 years, North Pacific mollusc harvests by Canada, China, Japan, and Korea have declined at statistically significant rates (Table 9-2). In contrast, North Pacific mollusc harvests by Russia and the USA have increased but remain a small share of total North Pacific mollusc harvests (Table 9-2).

Trends in the Russian and USA catch from the North Pacific are positive across all categories except for takes of marine mammals, which have declined. The observed increases in the Russian catch of diadromous fish, marine fish, and molluscs are statistically significant and substantial (Table 9-2). The increase in Russian catch of crustaceans from the North Pacific has been substantial (1,193 mt/year), as is the observed change in USA catch of crustaceans (2,180 mt/year) (Table 9-2). The observed trend in the USA catch of fish from the North Pacific is also statistically significant and substantial (25,961 mt/year); however, the increase is not statistically significant when fish catch is disaggregated to diadromous fish and marine fish categories (Table 9-2).

In contrast, trends in Japanese and Canadian catches from the North Pacific are negative (Table 9-2). In the case of Japan, these declines are statistically significant and substantial. In the

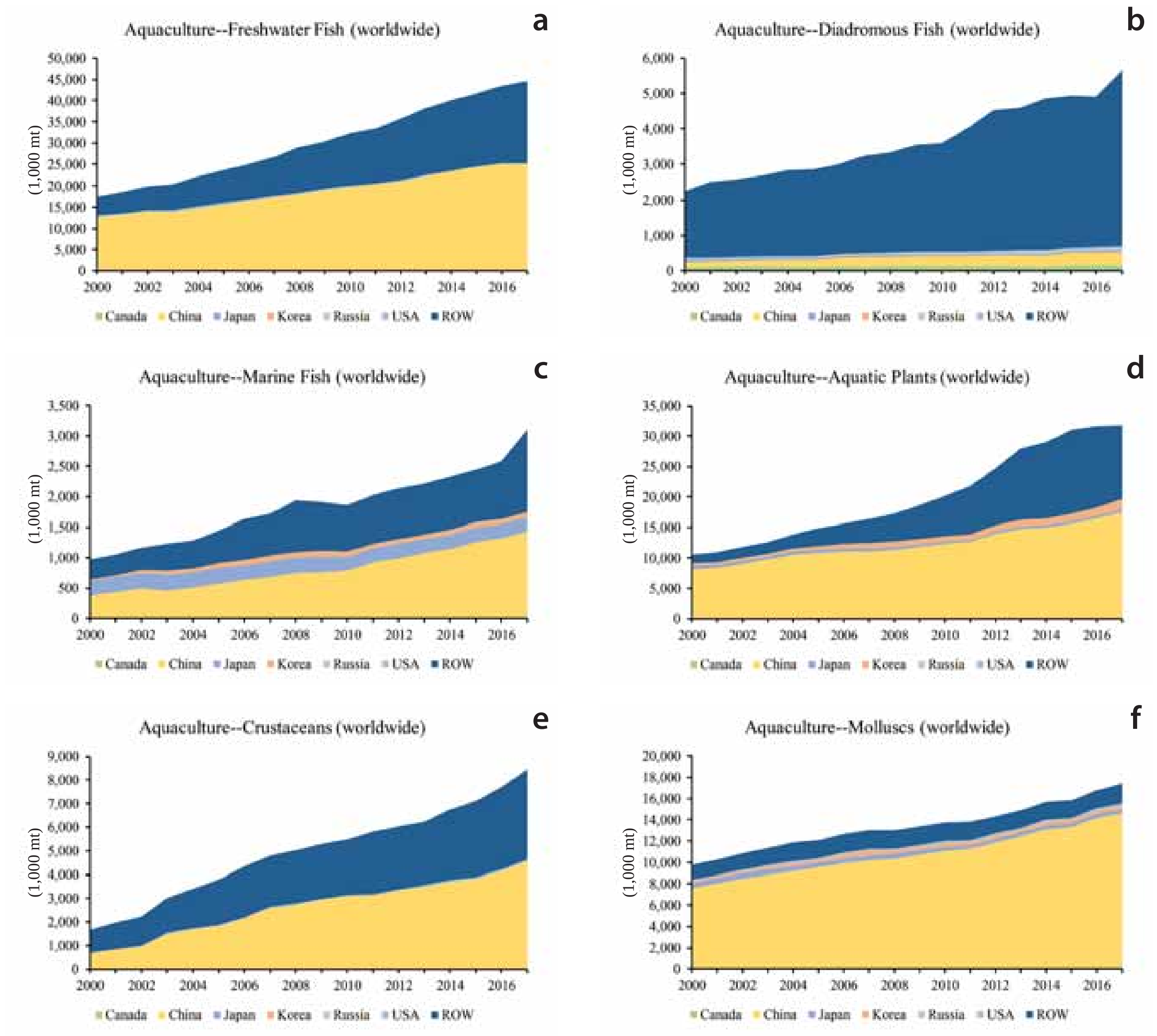

Figure 9-2. Annual worldwide production (in mt) from aquaculture: freshwater fish, diadromous fish, marine fish, aquatic plants, crustaceans, and molluscs, 2000–2017. Source: UN FAO Fish Stats (2020).

case of Canada, these declines are slight and not statistically significant, except for the mollusc catch where the decline is statistically significant and substantial as a percentage decline from mean historic catch levels.

Aquaculture

PICES member countries contribute significantly to global aquaculture production. Annual observations (2000–2017) of the total production of fish, crustaceans, and molluscs, and aquatic plants from aquaculture by PICES member countries and the ROW are shown in Figure 9-2. The annual mean (2000–2017) total aquaculture production of fish (with sub-groups diadromous fish, freshwater fish, and marine fish), crustaceans, and molluscs, and aquatic plants by PICES member countries and the ROW are reported in Table 9-3. Together, all six countries produce 59% of the global aquaculture supply of fish, 53% of the global aquaculture supply of crustaceans, 87% of the global aquaculture supply of molluscs, and 72% of the global aquaculture supply of aquatic plants (Table 9-3). Most of this production occurs in China (Figures 9-2a-f). Although aquaculture production increased at a statistically

Table 9-3. Annual mean (2000–2017) total aquaculture production (mt) by PICES member countries and all other countries (Rest-of-World, ROW). Source: UN FAO Fish Stats (2020).

	Diadromous fish	Freshwater fish	Marine fish	All fish	Crustaceans	Molluscs	Aquatic plants
Canada	124,315	-	-	124,315	-	37,316	-
China	260,590	18,632,803	810,926	19,704,319	2,620,361	10,777,928	12,241,398
Japan	48,744	4,860	243,397	297,001	1,673	409,456	455,464
Korea	9,800	7,122	75,119	92,041	2,850	335,520	869,353
Russia	28,902	94,930	1	123,832	6	1,449	949
USA	38,252	235,255	1,506	275,012	47,212	155,945	-
PICES nations	510,603	18,974,970	1,130,949	20,616,520	2,672,102	11,717,614	13,567,164
Non-PICES nations	3,153,167	11,171,737	703,958	15,028,861	2,273,759	1,660,011	6,479,619
Total	3,663,770	30,146,707	1,834,907	35,645,381	4,945,860	13,377,625	20,046,783

Table 9-4. Mean annual (2000–2017) percent (%) of the national and global catch taken from the North Pacific by PICES member countries and all other countries (ROW). Derived from UN FAO Fish Stats (2020).

	Diadromous fish (%)	Marine fish (%)	All fish (%)	Crustaceans (%)	Molluscs (%)	Marine mammals (%)
Canada	83.43	30.23	33.33	2.34	3.00	0.001
China	99.89	97.93	97.95	99.38	83.46	-
Japan	100.00	87.95	88.71	79.47	95.16	0.00
Korea	100.00	66.56	66.82	72.46	71.27	0.00
Russia	96.18	62.03	64.59	82.76	94.88	71.24
USA	98.68	65.28	68.36	23.69	2.65	50.50
PICES nations	98.11	81.72	82.45	78.86	66.99	5.24
Non-PICES nations	0.01	1.53	1.27	1.57	0.94	0.00
Total	53.89	25.75	23.43	41.05	35.30	2.02

significant rate in all categories from 2000–2017, it did not keep pace with the rate of increase in aquaculture production in the ROW in any categories except crustacean and mollusc aquaculture. For example, during that period, the PICES-region share of global aquaculture of diadromous fish declined at an average rate of 0.2 percentage points per year, for a loss of 3.6 percentage points over the 18 years.

Combined wild fisheries and aquaculture

The global supply of marine fish from wild harvests and aquaculture was relatively constant from 2000–2017. In contrast, there were substantial increases in the total production of freshwater fish in China (0.784 million mt/year) and ROW (1.189 million mt/year), and substantial increases in ROW production of diadromous fish (0.181 million mt/year). The net effect of these trends in fisheries and pisciculture is that the global supply of fish increased by about 34 million mt between 2000 and 2017 – a 34% increase primarily fueled by increased aquaculture production. During this period, the PICES share of global production increased for marine fish, all fish, crustaceans, and molluscs but declined for diadromous and freshwater fish. That is, the PICES region has become increasingly important to the global supply of marine fish, crustaceans, and molluscs, but is not keeping pace with the global expansion of diadromous and freshwater aquaculture.

Reliance on North Pacific wild fisheries

The extent to which PICES member countries and the ROW rely on catches from the North Pacific is represented as a share of wild fisheries in Table 9-4 and as a share of the total supply from aquaculture and wild fisheries in Table 9-5. Although the trend in Canada's overall catch of North Pacific fish remained nearly constant from 2000–2017, Canada's fish catch from other regions declined more rapidly so that Canada's dependence on fish catch from the North Pacific increased by over 10%. Finfish fisheries of Japan, Russia, the USA, and PICES as a whole, have also become increasingly reliant on the North Pacific. In contrast, Korea's finfish fishery has become less reliant on the North Pacific. Crustacean fisheries of the North Pacific have become less important to Canada, China,

Table 9-5. Mean annual (2000–2017) North Pacific catch as a percent (%) of total production by PICES member countries and all other countries (Rest-of-World, ROW). Derived from UN FAO Fish Stats (2020).

	Diadromous fish (%)	Marine fish (%)	All fish (%)	Crustaceans (%)	Molluscs (%)
Canada	15.41	30.23	26.39	2.34	2.26
China	26.23	89.83	30.97	47.90	11.52
Japan	79.18	81.22	81.03	78.17	60.37
Korea	47.44	62.55	61.98	70.70	38.24
Russia	87.29	62.03	62.36	82.75	93.48
USA	88.71	65.25	63.74	20.76	2.12
PICES	63.90	77.38	41.96	44.33	16.33
ROW	0.00	1.51	1.00	0.92	0.63
Global	17.75	25.04	16.06	23.52	12.39

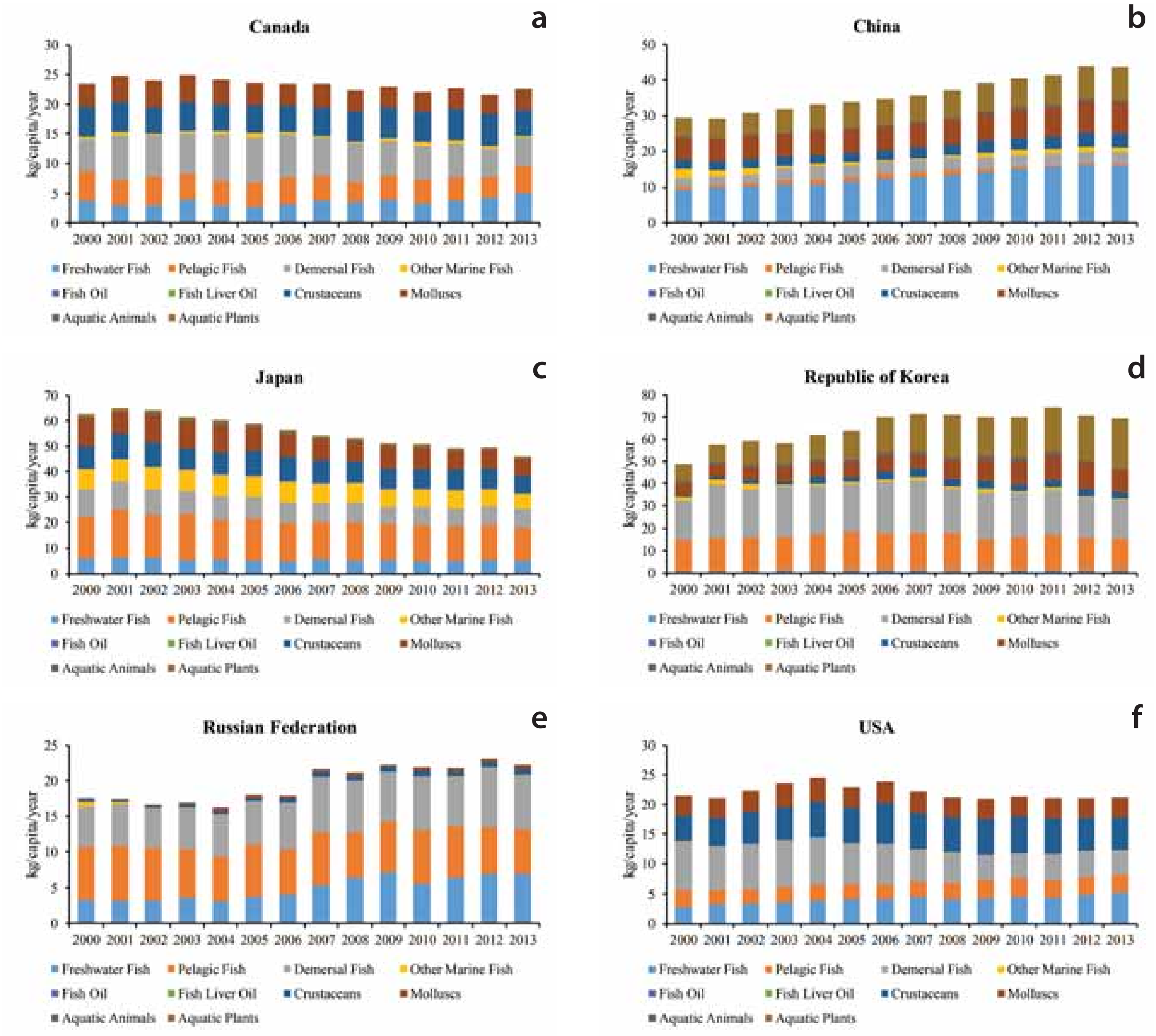

Figure 9-3. Per capita annual PICES member country consumption of aquatic products (kg/person/year), 2000–2013. Source: UN FAO Fish Stats (2020).

Table 9-6. Mean annual percent change (2000–2017) in the North Pacific catch as a percent (%) of total production by PICES member countries and all other countries (Rest-of-World, ROW). Derived from UN FAO Fish Stats (2020).

	Diadromous fish (%)	Marine fish (%)	All fish (%)	Crustaceans (%)	Molluscs (%)
Canada	–0.29	0.53*	0.19	–0.05	–0.09*
China	–1.26*	–0.48*	–0.73*	–2.31*	–0.54*
Japan	–0.64*	0.14*	0.10*	2.05*	0.10
Korea	–0.04	–0.51*	–0.51*	–0.28	–0.94*
Russia	–0.21	0.55*	0.54*	0.01	0.57*
USA	0.22*	0.29	0.48*	0.32*	0.08*
PICES nations	–0.57*	–0.03	–0.66*	–1.70*	–0.68*
Non-PICES nations	0.00*	0.02*	–0.01*	–0.04*	–0.03
Total	–0.48*	0.26*	–0.15*	–0.83*	–0.47*

* denotes values that are statistically significant at a 5% level.

and Korea, and more important to Japan, Russia, and the USA, although those trends are not statistically significant in the cases of Canada, Korea, and Russia. The importance of North Pacific mollusc fisheries has declined for Canada and China and increased for the remaining members of PICES.

The proportion of the North Pacific catch of diadromous fish to the global production from wild fisheries and aquaculture diminished from about 20% in the early 2000s to less than 13% in 2017 (Table 9-5). Canada, Japan, Russia, the USA, and the world as a whole have become increasingly reliant on North Pacific catch as a component of their supply of marine fish. China, Korea, and PICES as a whole have become less dependent on North Pacific catch as a component of their supply of marine fish (Table 9-6). For crustaceans and molluscs, the North Pacific catch has declined in importance as a component of production for Canada, China, Korea, PICES as a whole, and globally but has increased in importance for Japan, Russia, and the USA.

Consumption of aquatic products

Per capita annual consumption of aquatic products (kg/person/year) for PICES member countries and the ROW for 2000–2013, are shown in Figure 9-3. Between 2000 and 2013, Japanese per capita consumption of aquatic products declined by 13.1 kg for fish, 2.2 kg for crustaceans, 4.1 kg for molluscs, and 0.6 kg for aquatic plants, a rate of decline of –0.935 kg/year for fish, –0.154 kg/year for crustaceans, –0.294 kg/year for molluscs, and –0.042 kg/year for aquatic plants. Over this same period, per capita annual consumption of fish has also declined in Canada (–0.128 kg/year), Korea (–0.310 kg/year), and the USA (–0.178 kg/year. In contrast, per capita annual consumption of fish increased in China (0.565 kg/year) and Russia (0.470 kg/year). Per capita annual consumption of crustaceans increased in every member country except Japan. Per capita annual consumption of molluscs increased in China, Korea, and Russia, while decreasing in Canada, Japan, and the USA. From 2000–2013, the average per capita annual consumption of aquatic plants increased in China and Korea but decreased in Japan (data not available for Canada, USA, and Russia). It is noteworthy that Korean per capita annual consumption of aquatic plants increased by 16.2 kg between 2000 and 2013.

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