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## Preface

### Introduction

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 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 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 PICES Working Group 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 degrees, an area of over 35 million km<sup>2</sup>. 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 trophically dependent populations. The naming convention for the NPESR3 regions was established by the PICES Science Board at PICES-2016. Consistent with previous ecosystem status reports produced by PICES the third edition consists of chapters for each region (in a pdf format <https://meetings.pices.int/publications/special-publications>) 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 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 (including 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.

## Highlights

### 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 effectiveness of inherent, essentially chaotic, variability and of 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 growth, chemical processes such as deoxygenation, and the behaviour and condition 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 hundreds of years. Figure 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 2013, about midway through the 2009-2016 focal period.

A marine heatwave (MHW) occurred in the Northeast Pacific Ocean during 2014-16, 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 and its impacts on the 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 MHW. It is very likely there will be more MHWs in the future associated with large and disruptive biological responses and transitions in the structure and community 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). Because there are such 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 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 implication 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 Bering Strait in the summer as well as central Arctic influences.

There is growing interest in determining the predictability of the North Pacific Ocean, including associated biological responses, on time scales of months to years. Skillful forecasts would be of considerable value for management and other interests, of course, but there are additional, indirect benefits. The models that are being used for this purpose generally resemble those used to simulate the effects of climate change. In other words, 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 with forecasts out months to a few seasons 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 physical oceanographic conditions. Additional errors are introduced in the modeling 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 just 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 Climate and Ecosystem Predictability Working Group of PICES (WG40), (<https://meetings.pices.int/members/working-groups/wg40>).

Evidence of a changing climate seen in the sea surface temperature 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 other issues have emerged, such as the increase in microplastics pollution, the ecosystem consequences of the 2011 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 seabird die-offs highlight a potential shortage and or change in availability of typical planktonic and piscivorous prey of marine mammals and seabirds. 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 clean up activities.

## References

IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Stabeno et al. (2018): Distributed Biological Observatory region 1: Physics, chemistry and plankton in the northern Bering Sea. Deep Sea Research Part II: Topical Studies in Oceanography. doi: 10.1016/j.dsr2.2018.11.006.

Payne et al. (2017): Lessons from the first generation of marine ecological forecast products. Front. Mar. Sci., <https://doi.org/10.3389/fmars.2017.00289>

Seager and Simpson (2016): Western boundary currents and climate change. JGR Oceans, <https://doi.org/10.1002/2016JC012156>.

Sherman, K. and Hempel, G. (Editors) 2009. The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas. UNEP Regional Seas Report and Studies No. 182. United Nations Environment Programme. Nairobi, Kenya.

Siedlecki et al. (2016): Experiments with seasonal forecasts of ocean conditions for the Northern region of the California Current upwelling system. Sci. Rep. 6:27203. doi: 10.1038/srep27203

Yang et al. (2016): Intensification and poleward shift of subtropical western boundary currents in a warming climate, J. Geophys. Res. Oceans, 121, 4928–4945, doi:10.1002/2015JC011513.

Yatsu et al. (2013): Climate forcing and the Kuroshio/Oyashio ecosystem. ICES Journal of Marine Science, 70: 922–933.

## Figures

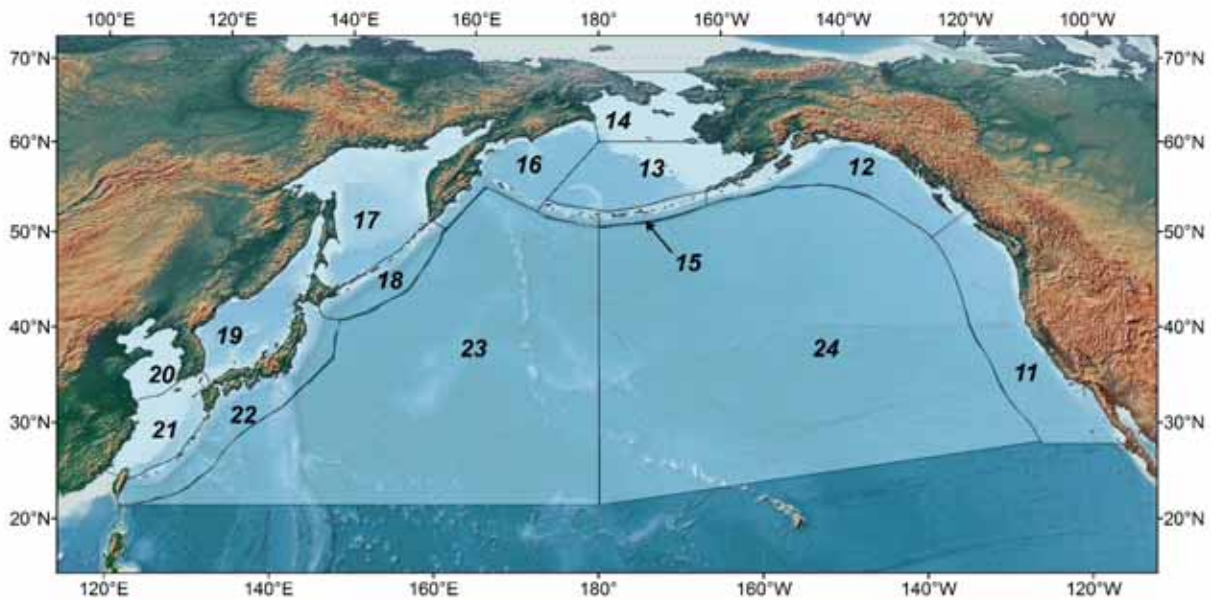


Figure 1. Map of the North Pacific Ocean showing the 14 regions and the PICES naming convention used in the regional ecosystem status reports that form the basis of the North Pacific Ecosystem Status Report (NPESR3).



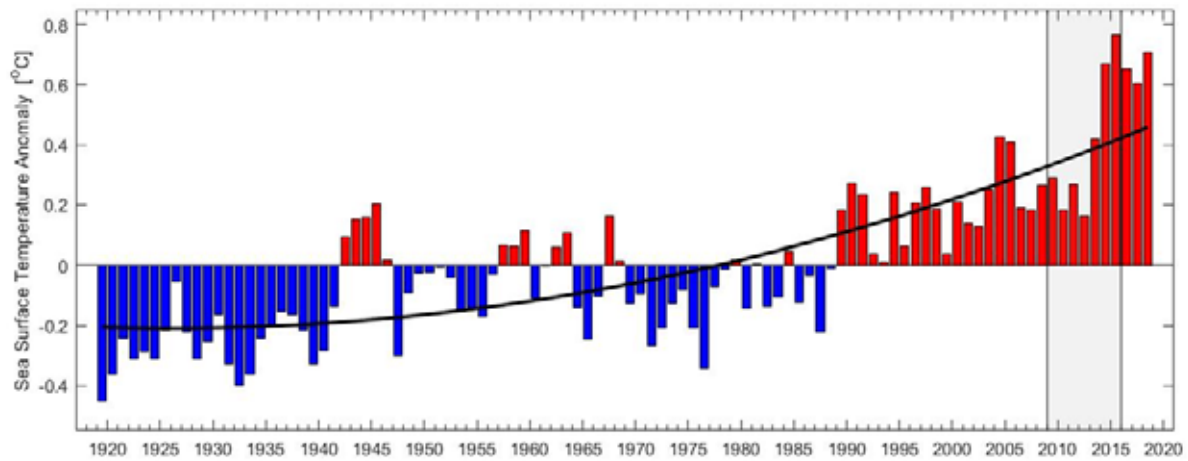


Figure 2. Time series of sea surface temperature (as the anomaly from the long-term average conditions) as provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at <https://www.esrl.noaa.gov/psd/>.

## Climate (Bond)

### Introduction

In the context of what we know about the climate system a 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 of 2009 through 2016; these volumes provide a wealth of information on atmospheric and oceanic conditions during the period of interest.

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 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 2009-10 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 2010-11 and to a lesser extent, during the winter of 2011-12. As is often the case during periods of La Niña, negative PDO conditions were present with cooler than normal SSTs in a band along the west coast of North America, and warmer than normal SSTs in the central North Pacific.

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 2014-15. A very strong El Niño did occur, but its onset was not until the summer of 2015. Nevertheless, the winters of 2014-15 and 2015-16 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 (MHW) that occurred in the Northeast Pacific Ocean during 2014-16 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 Nino/Southern Oscillation (ENSO) and the Aleutian Low

The correspondence between the state of El Nino/Southern Oscillation (ENSO) and the Aleutian low is a central tenet of North Pacific climate variability. Warm events in the tropical Pacific (El Ninos) during winter generally result in stronger mean Aleutian lows that are displaced to the southeast, and their counterparts (La Ninas) 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. 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 Ninos, 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 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 in the latter study 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 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 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. While perhaps they will not be as intuitive or as straightforward to implement, it is anticipated that techniques will be developed towards better characterization of North Pacific climate variability and its impacts on the ecosystem.

### References

- Captondi et al. (2015): Understanding ENSO Diversity. Bull. Amer. Meteor. Soc., 96:921–938, <https://doi.org/10.1175/BAMS-D-13-00117.1>
- Newman et al. (2016). The Pacific Decadal Oscillation, revisited. J. Climate, 29 (12), 4399–4427.
- Jacox et al. (2016): Forcing of multiyear extreme ocean temperatures that impacted California Current living marine resources in 2016. <https://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-17-0119.1>
- Kilduff et al. (2015): Changing central Pacific El Niños reduce stability of North American salmon survival rates. Proc Natl Acad Sci USA, 112(35):10962–10966.
- Litzow et al. (2018): Non-stationary climate-salmon relationships in the Gulf of Alaska. Proc. R. Soc. B, 285 (2018), 10.1098/rspb.2018.1855
- Walsh et al. (2016): The High Latitude Marine Heatwave of 2016 and Its Impacts on Alaska. <https://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-17-0105.1>
- Yun et al. (2015): Covariability of western tropical Pacific-North Pacific atmospheric circulation during summer. Sci. Rep., 5, 16980, <https://doi.org/10.1038/srep16980>.

## Figures

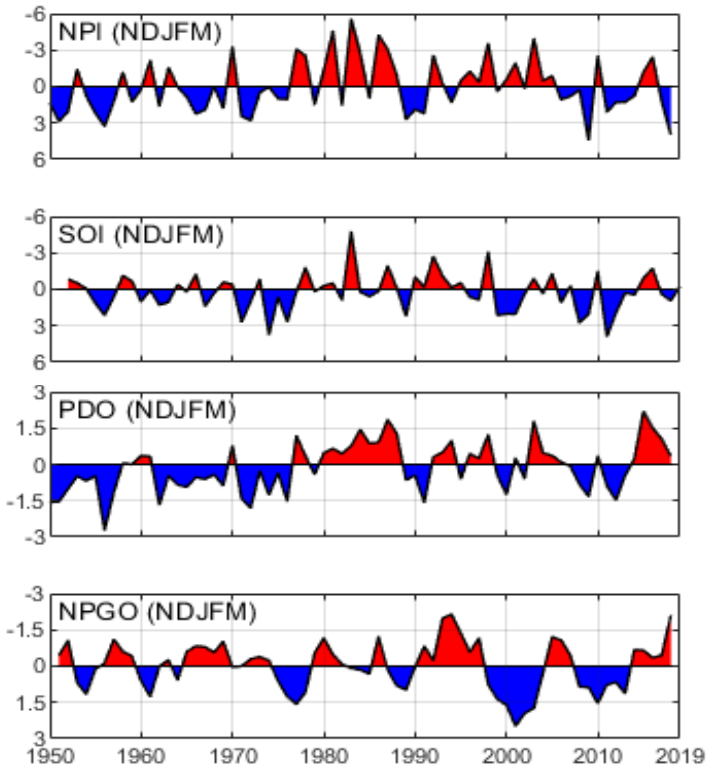


Figure 1. Time series of Pacific Ocean climate indices averaged over the months of Nov, Dec, Jan, Feb, and Mar. Some series are inverted (negative values are above the axes) so that all series are red when northeastern Pacific ocean temperatures are anomalously warm.

## The Physical Ocean [Chandler, Lobonov]

### Ocean Circulation

The upper ocean circulation of the North Pacific consists of rotating gyre systems primarily driven by atmospheric forcing (Figure 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 decades 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 sub tropical gyre results in a convergence zone at the southern edge of the North Pacific Transition Zone, associated with the southern boundary of the westerlies, where buoyant organic and inorganic matter aggregate. The nutrient-rich subarctic Pacific exports waters northward to the Arctic Ocean and southward to the subtropical Pacific, which significantly increases the productivity of these areas. The resulting Transition Zone Chlorophyll Front (TZCF) between the oceanic sub tropical and oceanic subarctic attracts many species of fish, marine mammals, and seabirds.

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, Grebmeier et al., 2015 ). The southward flowing Kamchatka Current mixes with water flowing from the Sea of Okhotsk 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 feed for fishes, whales and sea birds.

In 2013, winter winds, that 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  $1.6 \text{ ms}^{-1}$ , well below the 1948–2012 average of  $4.5 \pm 1.3 \text{ ms}^{-1}$ , and increasing the southerly component to  $4.7 \text{ ms}^{-1}$  from the average  $2.9 \pm 1.5 \text{ ms}^{-1}$  (Whitney, 2015). Consequently during the fall and winter of 2013 there was much less cooling of the surface waters than normal triggering the significant 2014-16 marine heatwave in the Northeast Pacific.

The North Pacific Subtropical High (NPSH) 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 east 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 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).

Sea level variability at a regional scale often corresponds to thermohaline changes. From 1993 to 2001 the increase in sea level in the region between Japan and Korea increases were nearly two times the global average due to thermohaline rise (Kang et al., 2005). In other cases regional sea level variability is associated with changing wind fields that change the ocean circulation (Kohl and Stammer, 2008). Along the west coast of North America climate patterns such as the El Niño-Southern Oscillation 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 large rates of sea level rise in the western tropical Pacific and of sea level fall in the eastern Pacific over the period 1993–2010 corresponded to an increase in the strength of the trade winds in the central and eastern tropical Pacific over the same period (Timmermann et al., 2010).

The melting of glaciers result in a rapid increase in the global mean sea level as the barotropic adjustment to the added mass (Gower, 2010). The gravitational and deformational effects following the loss of ice mass is expected to produce a spatial pattern of regional sea-level change. For example, melting from Alaska causing relative sea level to fall at decreasing rates from north to south along the west coast of North America, (National Research Council, 2012).

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 this period to more than 3 mm per year over the past decade or so.

Sea level rise varies geographically due to regional factors such as ocean and atmospheric circulation patterns, the gravitational and deformational effects of land ice mass changes, and tectonics along the coast. Sea level data from coastal tide gauges fixed to the land require correction for vertical land motions. For example, data from the tide gauge at Victoria, Canada, shows a sea level rise of about 6.8 cm/100 year; removing the influence of the tectonic uplift in the area gives a sea level rise of 12.6 cm/100 years (Figure 2).

The sea level data shown in Figure 3 are derived from time series of daily gridded observations with a horizontal resolution of 0.25°x0.25° obtained by merging altimetry measurements from two satellites provided by the Copernicus climate change service (C3S).

### Ocean Temperature and Salinity

The temperature and salinity of the 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 more influenced by currents. Additionally there is interannual and interdecadal variability associated with atmospheric systems, notably the El-Nino-Southern Oscillation (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°x2° Huang et al., 2015) is used to analyse the variability of the sea surface temperature for the 14 PICES regions. As seen in Figure 4 the temperature changes with the seasons, although there are clear differences in the annual range for each region.

Further analysis of these data (Figure 5) show how sea surface temperature, using the annual anomalies from the 30 year average (1989-2018), has changed over time. It can be seen that 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. The regional shift in SST is also evident in the NOAA ¼° resolution Optimum Interpolation Sea Surface Temperature (OISST) dataset when conditions from 2009-2012 are compared to those from 2013-2016. Figure 6 shows the sea surface temperatures as anomalies from the 1981-2010 climatology with a cool eastern ocean in the first half of the 2009-2016 period with a pattern representative of the Pacific Decadal Oscillation (PDO) in a negative phase. During the following three years (2013-2016) the northeastern 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 are 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 provides near continuous time series of temperature and salinity for the upper 2000 m of the ocean. At the



position of the long-term ocean monitoring station Papa (50°N, 145°W) in the Gulf of Alaska profile information from the surrounding Argo floats has been interpolated to show normalized temperature anomalies versus time and depth (Figure 7, 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 the 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.

The corresponding time series of Argo density data is shown in the lower panel of Figure 7. The annual winter mixing of the upper ocean, as indicated by the depth of the 1025.7 kgm<sup>-3</sup> 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 7 and 8 show the regional variability of sea surface salinity, in a similar format used for SST in Figures 4 and 5. The source of the salinity data is the EN4 dataset from the Joint DECC/Defra Met Office Hadley Centre (Good et al., 2013).

#### [Ocean Acidification and Deoxygenation](#)

See PICES special publication 5

#### [Upwelling](#)

Upwelling, the vertical transport of nutrient-rich cold waters into the sunlit euphotic zone of the coastal ocean, is an important driver of primary production. In the California Current upwelling is driven by northwesterly winds coupled with the Coriolis force, resulting in offshore and vertical advection (Huyer 1983). The intensity of upwelling along the coast varies as spatially-segregated “upwelling jets” form due to the local bathymetry at the shelf break (Chakk and Di Lorenzo 2007).

Alongshore winds driven by atmospheric pressure systems in the Gulf of Alaska shift from predominantly poleward in winter to predominantly upwelling-favourable equatorward winds in summer. This timing of this shift is referred to as the Spring Transition and the reverse process in fall is called the Fall Transition. A measure of the strength of upwelling is derived by summing upwelling-favourable-only wind stresses along the west coast of North America from 45°-60° N using the NCEP/NCAR Reanalysis-1 analyses (Kistler et al. 2001) and subtracting the long-term mean. Figure 10 shows the monthly mean upwelling anomalies, and that periods of

stronger-than-average upwelling occur during each year except 2014 which was generally below average.

Figure 11 shows the annual upwelling-favourable wind stress magnitude and the timing of the transitions between upwelling-favourable and downwelling-favourable conditions. Generally an earlier, longer, and more intense upwelling season relates to greater primary productivity. Based on these factors upwelling conditions during the 2009-2016 focal period have varied but there have been no clearly productive or unproductive years.

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 primarily driven by alongshore winds, and enhanced by local bathymetry. Upwelling off the northeastern part of Taiwan Island, 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 influence the dynamic balance between the meandering Kuroshio current and coastal water from the south flowing onto the continental shelf.

### 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 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 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 implication 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 Bering Strait in the summer as well as central Arctic influences.

Sea ice that forms in the Arctic proceeds south 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 2011). Sea ice begins to retreat in late winter or early spring and is absent by late June; its extent and duration are critical influencers of ice algae and phytoplankton primary production.

Based on the analysis of Serreze et al., 2016 the beginning of the open water period on 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 12 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 13 shows the interannual variability (attributed to changes in regional atmospheric conditions, sea surface temperature and salinity) of the mean ice cover in the Bering Sea and the Tartar Strait with no clear long-term trend. In PICES region 17 (the Sea of Okhotsk) the baseline ice cover from January to May is based on observations since 1960. Reduced ice cover has been evident since 1984, and has been consistently below normal between 2009 and 2016. Even in the coldest winter of 2011-2012, the ice cover did not reach its normal level with only about 80 % of the Okhotsk Sea occupied by ice (Figure 14).

Ice conditions in the West Kamchatka area are crucially important for the winter fishery in the Okhotsk Sea, and there was low ice cover in this area over the 2009-2016 focal period. 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 crucially 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 late forming they were relatively large and stable in 2010, 2014, and 2015 and these years were relatively favourable for the herring spawning.

## References

- Aagaard, K., Weingartner, T., Danielson, S. L., Woodgate, R. A., Johnson, G. C., and Whitledge, T. E. ( 2006), Some controls on flow and salinity in Bering Strait, *Geophys. Res. Lett.*, 33, L19602, doi:10.1029/2006GL026612.
- Grebmeier, J.M., B.A. Bluhm, L.W. Cooper, S.G. Denisenko, K. Iken, M. Kędra, and C. Serratos. 2015. Time-series benthic community composition and biomass and associated environmental characteristics in the Chukchi Sea during the RUSALCA 2004–2012 Program. *Oceanography* 28:116–133, <https://doi.org/10.5670/oceanog.2015.61>.
- Ferrari, R., and D. Ferreira, 2011. What processes drive the ocean heat transport?, *Ocean Modelling*, 38 (3-4), 171–186, doi:10.1016/j.ocemod.2011.02.013.
- Whitney, F. A. (2015), Anomalous winter winds decrease 2014 transition zone productivity in the NE Pacific, *Geophys. Res. Lett.*, 42, 428–431, doi:10.1002/2014GL062634.

Qiu B. and Chen S., 2005. Variability of the Kuroshio extension jet, recirculation gyre, and mesoscale eddies on decadal time scales. *J. Phys. Oceanogr.*, 35 (2005), pp. 2090-2103

Howell, E.A, S. J. Bograd, C. Morishige, M. P. Seki, J. J. Polovina, 2012, On North Pacific circulation and associated marine debris concentration. *Marine Pollution Bulletin*. Volume 65, Issues 1–3, pp 16-22. <https://doi.org/10.1016/j.marpolbul.2011.04.034>

Wu, L., Cai, W., Zhang, L., Nakamura, H., Timmermann, A., Joyce, T., McPhaden, M. J., et al. 2012. Enhanced warming over the global subtropical western boundary currents. *Nature Climate Change*, 2: 161–166.

Yasuda, I., 1997. The origin of North Pacific Water. *J. Geophys. Res.* 102, 893-909.

Gower, J. F. R. (2010), Comment on “Response of the global ocean to Greenland and Antarctic ice melting” by D. Stammer, *J. Geophys. Res.*, 115, C10009, doi:10.1029/2010JC006097.

Kang, S. K., J. Y. Cherniawsky, M. G. G. Foreman, H. S. Min, C. H. Kim, and H. W. Kang, 2005: Patterns of recent sea level rise in the East/Japan Sea from satellite altimetry and in situ data. *J. Geophys. Res. Oceans*, 110, C07002. Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura,

Kohl, A., and D. Stammer, 2008: Decadal sea level changes in the 50-year GECCO ocean synthesis. *J. Clim.*, 21, 1876–1890.

Timmermann, A., S. McGregor, and F. F. Jin, 2010: Wind effects on past and future regional sea level trends in the Southern Indo-Pacific. *J. Clim.*, 23, 4429–4437.

National Research Council. 2012. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Washington, DC: The National Academies Press. <https://doi.org/10.17226/13389>.

Serreze, M. C., Crawford, A. D., Stroeve, J. C., Barrett, A. P., and Woodgate, R. A. ( 2016), Variability, trends, and predictability of seasonal sea ice retreat and advance in the Chukchi Sea, *J. Geophys. Res. Oceans*, 121, 7308– 7325, doi:10.1002/2016JC011977.

Sigler, M.F., M. Renner, S.L. Danielson, L.B. Eisner, R.R. Lauth, K.J. Kuletz, E.A. Logerwell, and G.L. Hunt Jr. 2011. Fluxes, fins, and feathers: Relationships among the Bering, Chukchi, and Beaufort Seas in a time of climate change. *Oceanography* 24:250–265, <https://doi.org/10.5670/oceanog.2011.77>.

Stabeno et al. (2018): [Distributed Biological Observatory region 1: Physics, chemistry and plankton in the northern Bering Sea](#). *Deep Sea Research Part II: Topical Studies in Oceanography*. doi: 10.1016/j.dsr2.2018.11.006.

Good, S. A., M. J. Martin and N. A. Rayner, 2013. EN4: quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates, *Journal of Geophysical Research: Oceans*, 118, 6704-6716, doi:10.1002/2013JC009067

Chhak, K., and Di Lorenzo, E. 2007. Decadal variations in the California Current upwelling cells. *Geophys. Res. Lett.* 34: L14604.

Huyer, A. 1983. Coastal upwelling in the California Current System. *Prog. Oceanogr.* 12: 259-284.

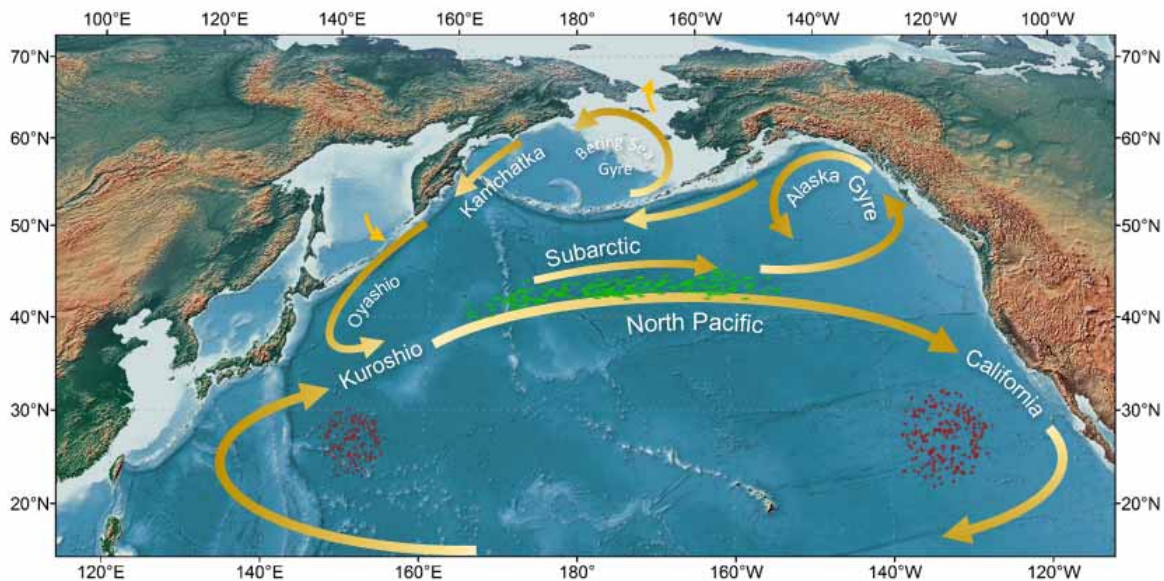
Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woolen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van del Dool, H., Jenne, R., and Fiorino, M. 2001. The NCEP–NCAR 50-year reanalysis: monthly means CD-ROM and documentation. *Bulletin of the American Meteorological Society* 82: 247–267.

Lou, X. L., A. Q. Shi, Q. M. Xiao, and H. G. Zhang (2011), Satellite observation of the Zhejiang coastal upwelling in the East China Sea during 2007–2009, *Proc. SPIE*, 8175(2), 283–304.

Tseng, Y.-H., M.-L. Shen, S. Jan, D. E. Dietrich, and C.-P. Chiang (2012), Validation of the Kuroshio Current System in the dual-domain Pacific Ocean, *Prog. Oceanogr.*, 105, 102–124

Wong, G. T. F., S.-Y. Chao, Y.-H. Li, and F.-K. Shiah (2000), The Kuroshio edge exchange processes (KEEP) study—An introduction to hypotheses and highlights, *Cont. Shelf Res.*, 20, 335–347.

## Figures



*Figure 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.*

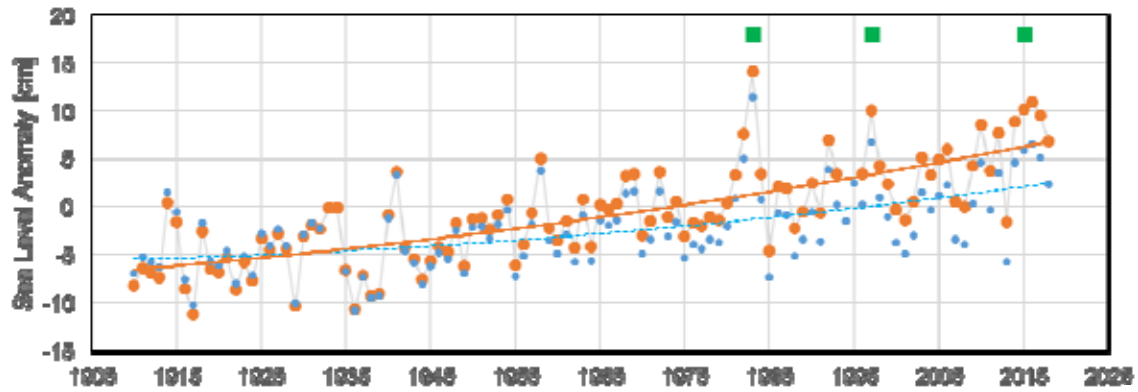


Figure 1 Tide gauge data from the Canadian Hydrographic Service in Victoria, Canada , corrected with uplift data from the Pacific Geoscience Centre, BC, Canada. Blue dots are uncorrected data, orange are corrected data, green squares show timing of strong El-Nino events.

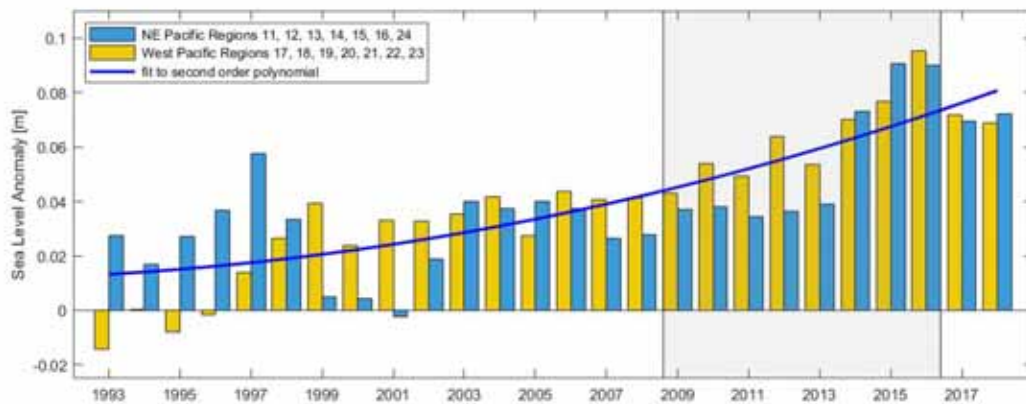


Figure 2. Annual sea level anomaly computed with respect to a 20-year mean reference period (1993-2012) combined for PICES regions in the western and Northeast Pacific from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global>.



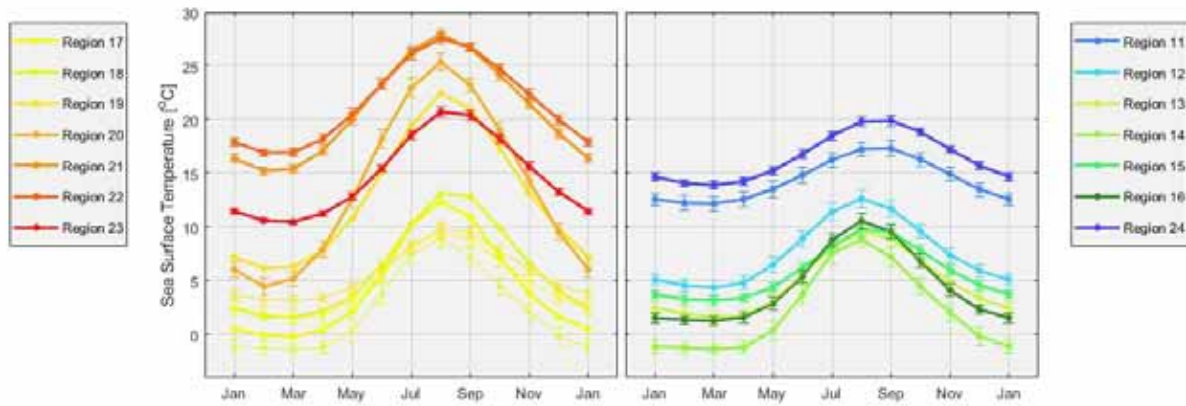


Figure 4. The average monthly sea surface temperature for each PICES region based on 30 years of ERRST data, 1989-2018.. The error bars represent the standard deviation.

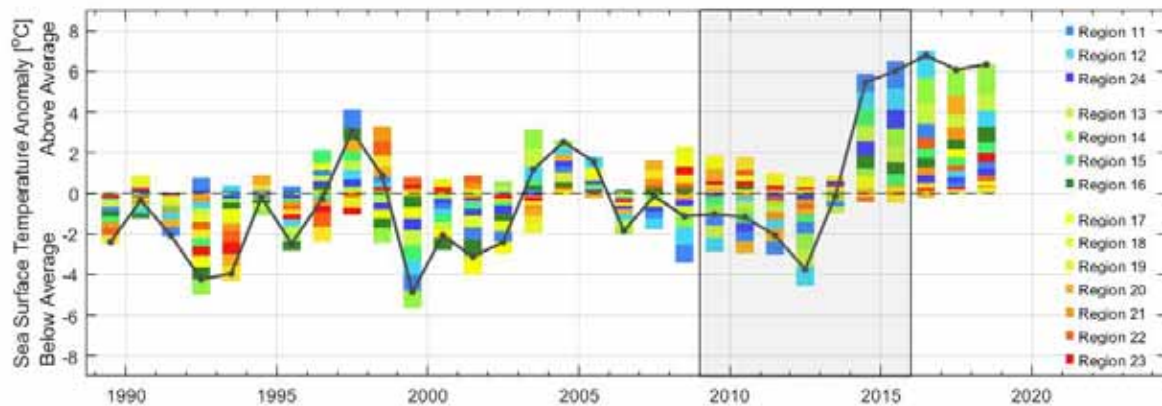


Figure 5. The annual sea surface temperature anomalies for each PICES region based on 30 years of NOAA Extended Reconstructed Sea Surface Temperature (SST) V4 (ERSST). For each year the anomalies are ordered from top to bottom by the magnitude of the anomaly. The black line represents the combined anomalies for all regions.

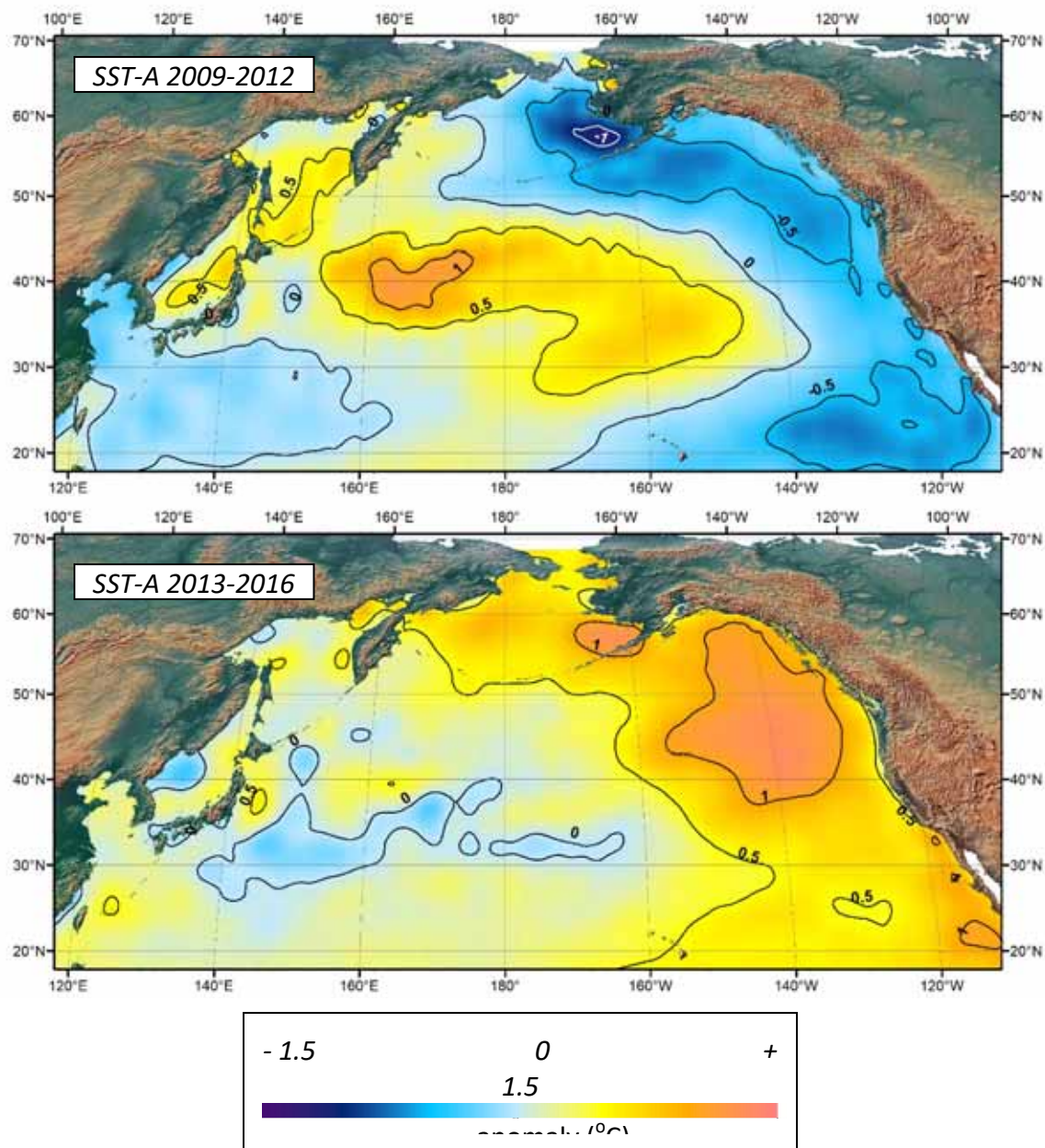


Figure 6. Sea surface temperature anomaly maps showing an SST pattern consistent with a negative PDO phase in 2009-2012 (upper panel), and the change to a positive phase PDO pattern in 2013-2016 (lower panel).



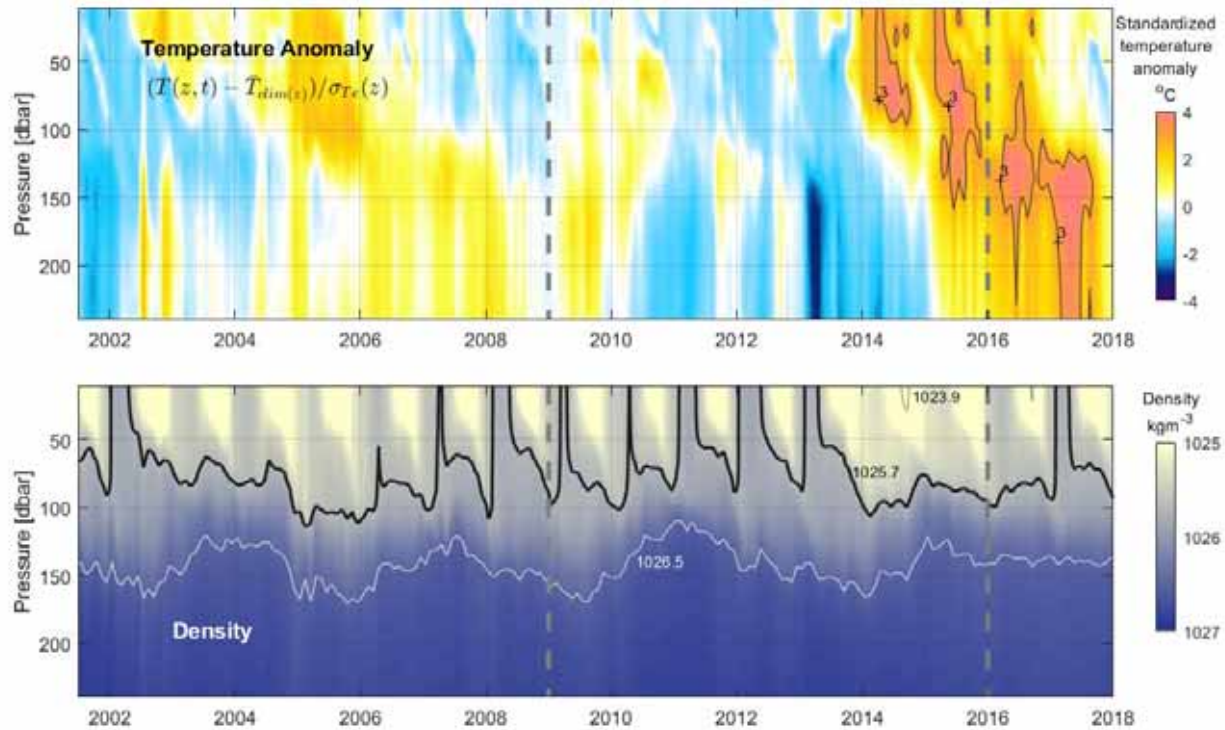


Figure 7. Upper panel. Temperature anomalies of Argo data observed near Station Papa relative to the 1956-2012 seasonally-corrected data from Station Papa. Black lines show regions with anomalies 3 standard deviation above the mean. Lower panel. Density observed by Argo floats near Station Papa. The thick black line shows the 1025.7 kgm<sup>-3</sup> isopycnal. 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.

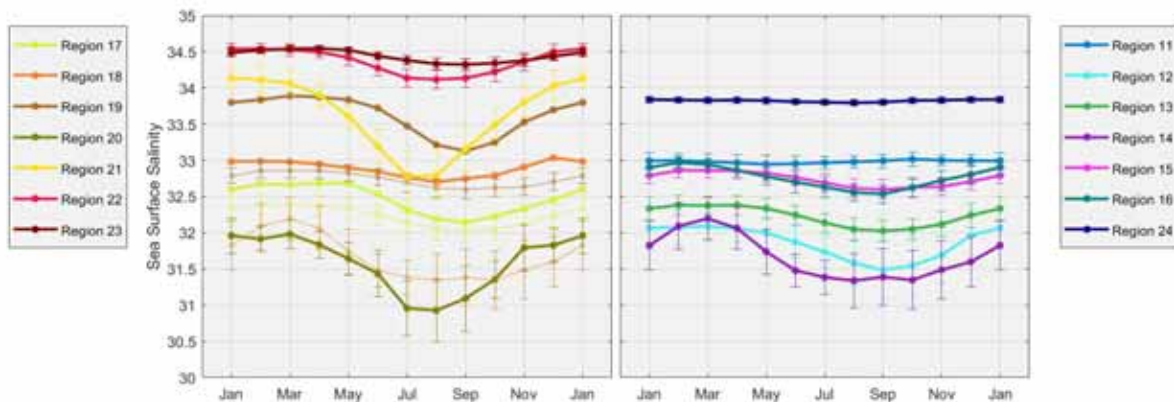


Figure 8. The average monthly sea surface salinity for each PICES region based on 25 years of Met Office Hadley Centre data, 1993-2018.. The error bars represent the standard deviation.

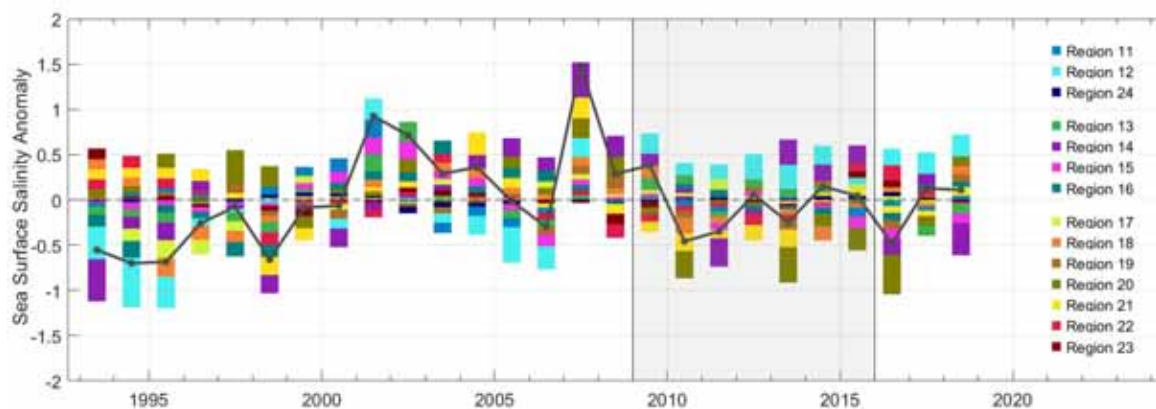


Figure 9. The annual sea surface salinity anomalies for each PICES region based on 25 years of Met Office Hadley Centre data . For each year the anomalies are ordered from top to bottom by the magnitude of the anomaly. The black line represents the combined anomalies for all regions.

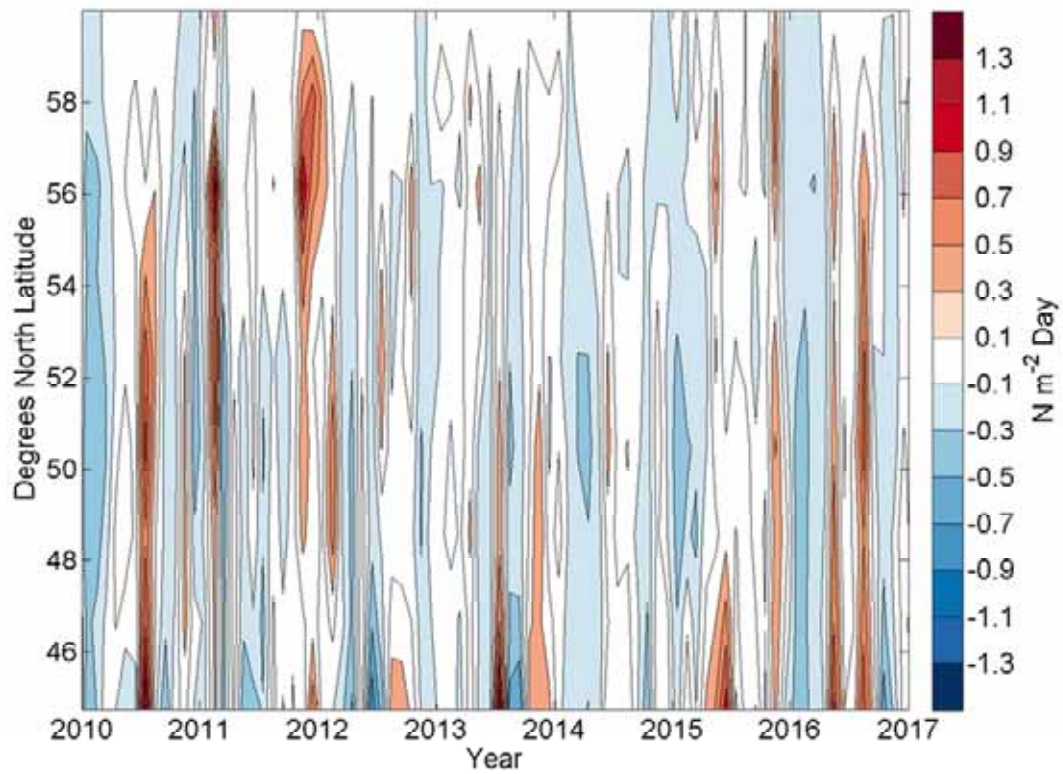


Figure 10. Monthly mean anomalies of alongshore upwelling-favourable (equatorward) wind stress at coastal grid points from 45-60° N.

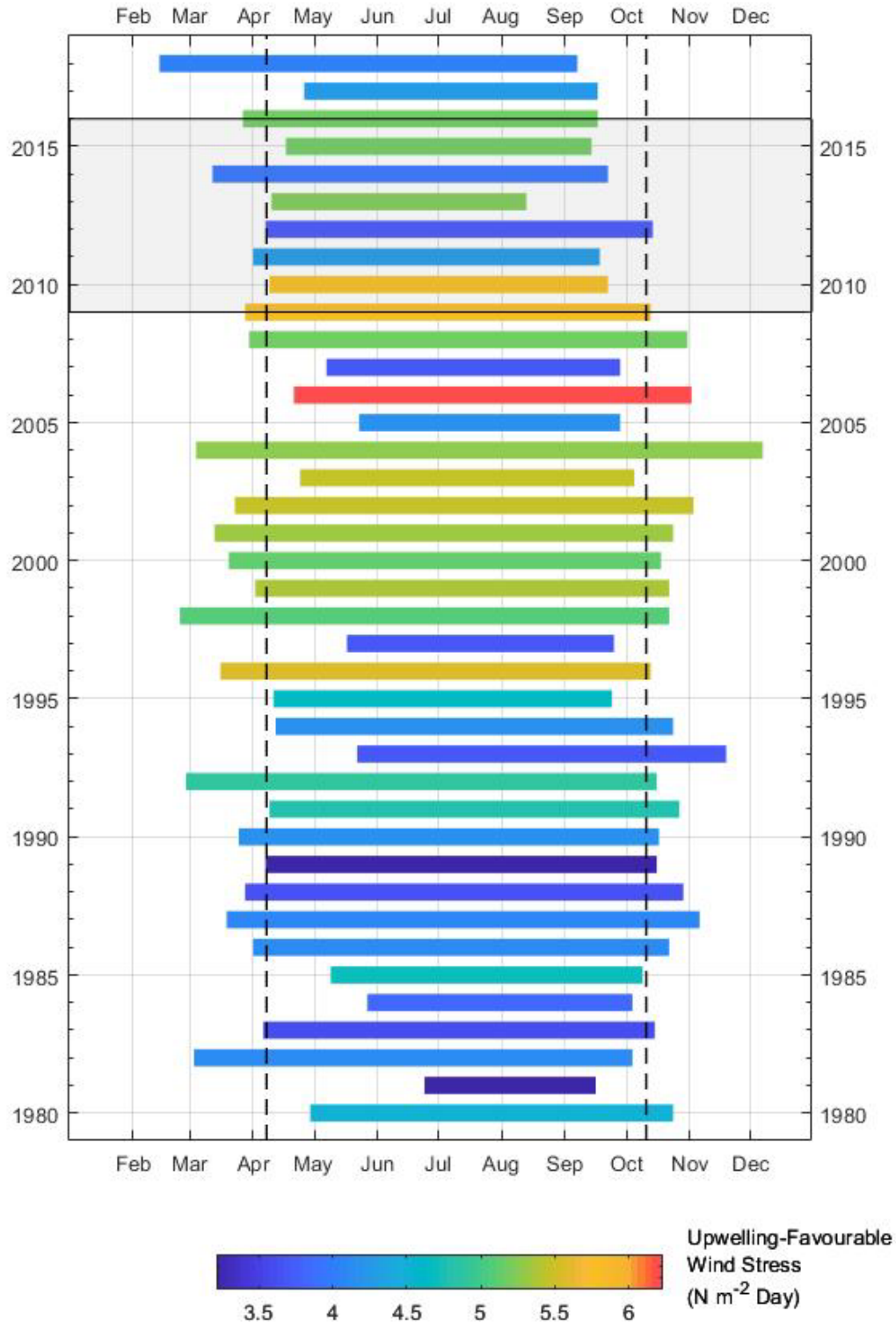


Figure 11. The upwelling favourable wind stress index on the west coast of North America (49°N, 126°W). The length of the bar corresponds to the duration of the upwelling season, coloured by the intensity of the upwelling. The dashed lines indicate the average start and end of the upwelling season. Data source: NOAA/OAR/ESRL/Physical Sciences Division

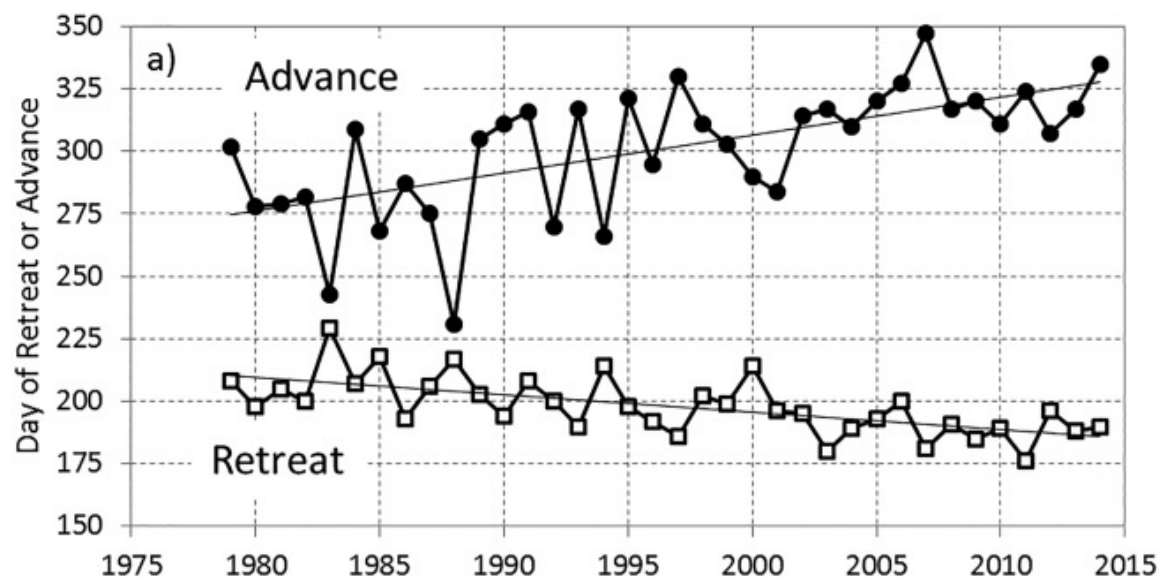


Figure 12. Time series and linear trends of sea ice retreat and advance along the northern boundary of the Bering Sea (adapted from Serreze et al., 2016).

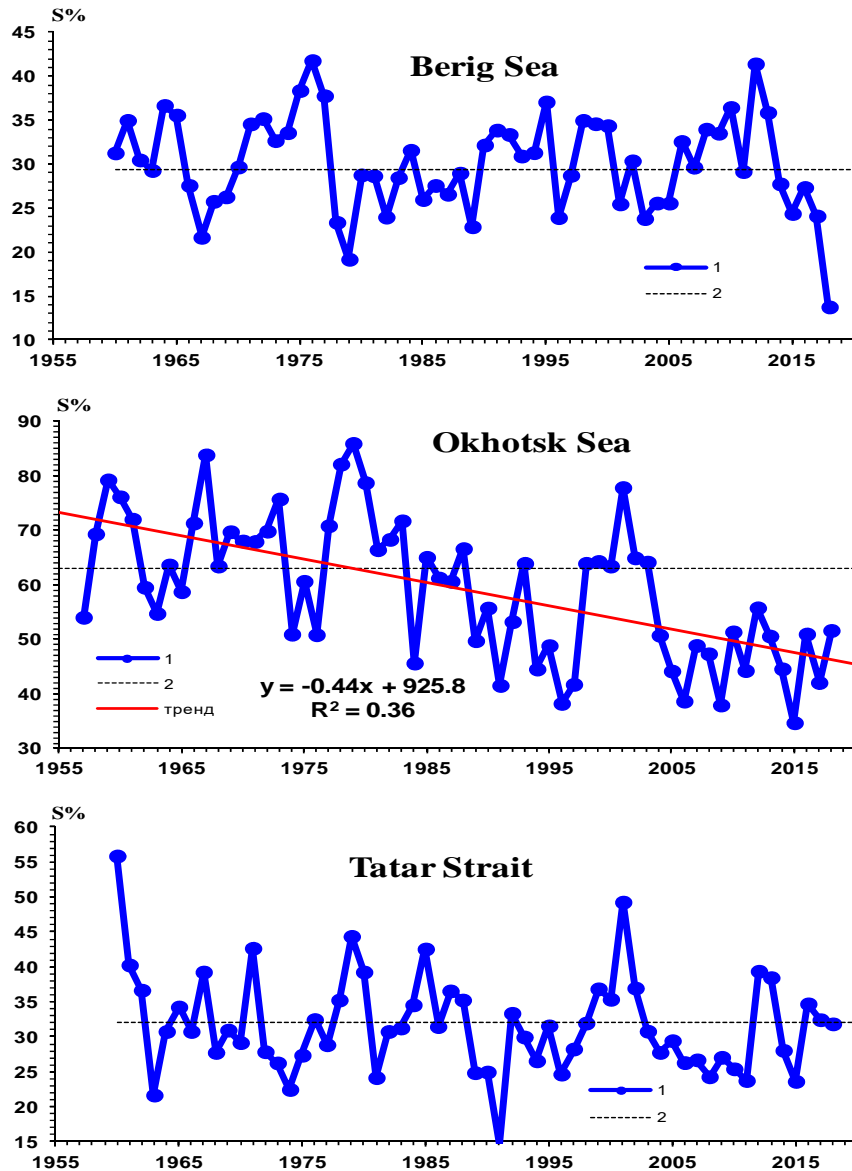


Figure 13. Mean winter ice cover in the Bering and Okhotsk Sea and in the Tatar Strait (1), mean multi-year value (2) and statistically significant (99%) trend. S% is a percent of the ice covered area to the whole area of the sea. (Ustinova and Sorokin, 2013 with additional data by the authors)

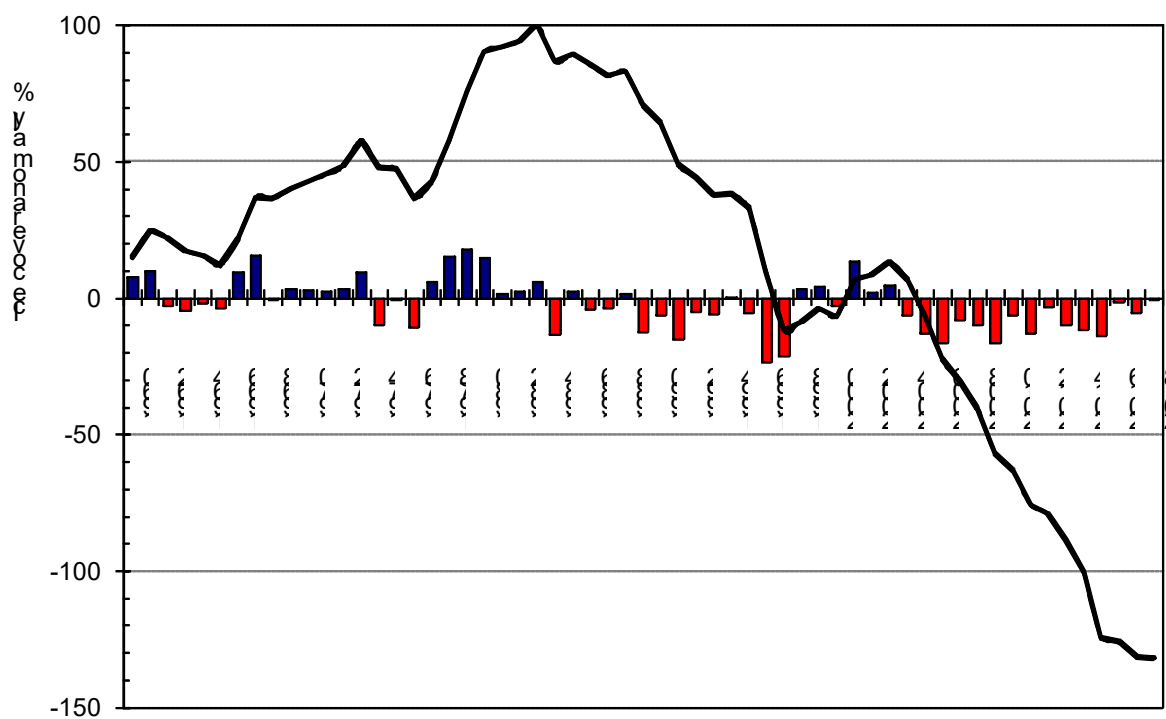


Figure 14. Mean ice cover anomalies (relative to the 1960 – 2017 baseline data) and the cumulative ice cover curve for the Sea of Okhotsk.



## The Chemical Ocean [Ono, Kivva]

In this section the essential nutrients that support primary production are examined. Dissolved oxygen (DO) and carbonate parameters (pH, total alkalinity DIC and pCO<sub>2</sub>) are also described but the reader is referred to the recent and comprehensive review provided in PICES Special Publication 5, Ocean Acidification and Deoxygenation in the North Pacific Ocean (Christian and Ono, 2019).

As described in NPESR2 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 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. PDO and NPGO). In coastal regions changes in anthropogenic loading of nutrients and organic substances provided an additional cause of deoxygenation and ocean acidification.

### Deoxygenation

A synthesis of deoxygenation trends derived from NPESR3 regional reports is given in Table xxx showing subsurface deoxygenation in many regions of the North Pacific. There are exceptions, such as the Alaskan coastal region and the Bering Sea, but this is more likely due to lack of data and indicates an insufficient monitoring system rather than a different oxygen process.

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 such that at the water depth below the surface layer (the pycnocline) there is a trend of deoxygenation and nutrient accumulation (Whitney et al., 2013).

The relationship between decreasing 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 variations show an influence by the PDO and NGPO (Yasunaka et al., 2016, Di Lorenzo et al., 2008), and specific areas, such as the Oyashio region (R18) and the western Subarctic Gyre, are additionally influenced by the NPI and the 18.6 year nodal tidal cycle.

An increase in DO in layers just below the seasonal pycnocline (50-300 m) has been observed recently in several regions including California Current (R11), Sea of Okhotsk (R17), Oyashio region (R18), Yellow Sea (R20) and Western Subarctic Gyre (R23). 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 and nutrients in the surface layer due to extreme winter cooling and convection along the eastern coast of Asia. Since 2009 increased dissolved oxygen levels have been observed in the deep waters off the coast of British Columbia (Crawford, 2017). 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 the Yellow Sea (R20) 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 mobilizes N and P 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 larger 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 due to changes of ratios between inorganic nutrients (e.g. Justic et al., 1995) which can dramatically change community structures. These changes directly and indirectly affect protected species, commercial fish stocks and may lead to harmful algal blooms.

Eutrophication is most prominent in the Yellow Sea (R20) and East China Sea (R21) where significant nutrient loads are introduced to coastal waters by large rivers and wind, and is well documented in 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 the Yellow and East China Seas. For instance, there is an evidence of riverine nutrient discharge increase and bottom hypoxia in the Salish Sea area (coastal British Columbia, Canada, R12) (Khangaonkar et al., 2018, 2019).

### Ocean Acidification

As seen in Table 1 many of the PICES regions have too few pH data time series to examine trends. In those regions where data are available ocean acidification (OA) has been detected both in surface waters and subsurface waters. All subsurface OA trends are associated with deoxygenation trends confirming that OA trends are not caused only by a temporal increase of atmospheric CO<sub>2</sub> but also results from reduction of water ventilation (e.g., Rios et al., 2015). This combined stress of both OA and deoxygenation are expected to cause more severe impacts on marine organisms (Portner and Farrell, 2008).

## References

- Christian, J.R., and Ono, T. [Eds.] 2019. Ocean Acidification and Deoxygenation in the North Pacific Ocean. PICES Special Publication 6, 101pp.
- Crawford, W.E., 2017. State of the Pacific Ocean report.
- Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Marine ecology progress series, 210, pp.223-253.
- Di Lorenzo, E., Schneider, N., Cobb, K M., Franks, P J S., Chhak, K., Miller, A J., McWilliams, J C., Bograd, S J., Arango, H., Curchitser, E., Powell, T M., and Riviere, P. 2008. North Pacific gyre oscillation links ocean climate and ecosystem change. Geophysical Research Letters, 35: L08607. 10.1029/2007GL032838
- Jiang, Z., Liu, J., Chen, J., Chen, Q., Yan, X., Xuan, J. and Zeng, J., 2014. Responses of summer phytoplankton community to drastic environmental changes in the Changjiang (Yangtze River) estuary during the past 50 years. Water Research, 54, pp.1-11.
- Justić, D., Rabalais, N.N. and Turner, R.E., 1995. Stoichiometric nutrient balance and origin of coastal eutrophication. Marine pollution bulletin, 30(1), pp.41-46.
- Khangaonkar, T., Nugraha, A., Xu, W., Long, W., Bianucci, L., Ahmed, A., Mohamedali, T. and Pelletier, G., 2018. Analysis of hypoxia and sensitivity to nutrient pollution in Salish Sea. Journal of Geophysical Research: Oceans, 123(7), pp.4735-4761.
- Khangaonkar, T., Nugraha, A., Xu, W. and Balaguru, K., 2019. Salish Sea Response to Global Climate Change, Sea Level Rise, and Future Nutrient Loads. Journal of Geophysical Research: Oceans.
- Ning, X, Lin, C., Su, J., Liu, C., Hao, Q., and Le, F, 2011. Long-term changes of dissolved oxygen, hypoxia, and the responses of the ecosystems in the East China Sea from 1975 to 1995. Journal of Oceanography 67: 59-75. 10.1007/s10872-011-0006-7
- Nixon, S.W., 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia, 41(1), pp.199-219.
- Paerl, H.W., 1997. Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as “new” nitrogen and other nutrient sources. Limnology and oceanography, 42(5part2), pp.1154-1165.
- Portner, H O., and Farrell, A P. 2008. Physiology and climate change. Science 322: 690-692. 10.1126/science.1163156
- Radchenko, V.I., Dulepova, E.P., Figurkin, A.L., Katugin, O.N., Ohshima, K., Nishioka, J., McKinnell, S.M., Tsoy, A.T. 2010. Status and trends of the Sea of Okhotsk region, 2003-2008, pp.

268-299 In S.M. McKinnell and M.J. Dagg [Eds.] *Marine Ecosystems of the North Pacific Ocean*, 2003-2008. PICES Special Publication 4, 393 p.

Rios, A F., Resplandy, L., Garcia-Ibanez M I., Fajar, N M., Velo, A., Padin, X A., Wanninkhof, R., Steinfeldt, R., Roson, G., and Perez, F F. 2015. Decadal acidification in the water masses of the Atlantic Ocean. *PNAS* 112: 9950-9955. 10.1073/pnas.1504613112

Schmidtko, S., Stramma, L., and Visbeck, M., 2017. Decline in global oceanic oxygen content during past five decades. *Nature* 542: 335-339. 10.1038/nature21399

Stramma, L., Schmidtko, S., Bograd, S. J., Ono, T., Ross, T., Sasano, D., and Whitney, F. A., 2019. The influence of decadal oscillations on the oxygen and nutrient trends in the Pacific Ocean. *Biogeoscience Discussion*, 10.5194/bg-2019-91

Takatani, Y., Sasano, D., Nakano, T., Midorikawa, T., and Ishii, M., 2012. Decrease of dissolved oxygen after the mid-1980s in the western North Pacific subtropical gyre along the 137°E repeat section. *Global Biogeochemical Cycles* 26: GB2013. 10.1029/2011GB004227

Xing, Q., Tosi, L., Braga, F., Gao, X. and Gao, M., 2015. Interpreting the progressive eutrophication behind the world's largest macroalgal blooms with water quality and ocean color data. *Natural Hazards*, 78(1), pp.7-21.

Yasunaka, S., Ono, T., Nojiri, Y., Whitney, F A., Wada, C., Murata, A., Nakaoka, S., and Hosoda, S. 2016. Long-term variability of surface nutrient concentrations in the North Pacific. *Geophysical Research Letters*, 43: 3389-3397. 10.1002/2016GL068097

Whitney, F. A., Bograd, S. J., and Ono, T., 2013. Nutrient enrichment of the subarctic Pacific Ocean pycnocline. *Geophysical Research Letters* 40: 1-6. 10.1002/grl.50439

Zhang, J., S. Liu, J. Ren, Y. Wu, and G. Zhang (2007), Nutrient gradients from the eutrophic Changjiang (Yangtze River) Estuary to the oligotrophic Kuroshio waters and re-evaluation of budgets for the East China Sea Shelf, *Progress in Oceanography*, 74(4), 449-478

Table 1 list of long-term variation of nutrient / oxygen / pH shown in each regional report. Plus and minus mark represents positive and negative trend, respectively.

Area	about long-term variation			
	nutrient/surface	nutrient/subsurfa	oxygen/subsurfac	pH/subsurface
11			– (1980-2000) + (2000-2018)	
12				
13	–			
14				
15	+			
16				
17			–	
18	+	–	–	–
19			–	–
20		+	–	
21				
22				
23	–	+	–	–
24			–	

## Phytoplankton [Yoo, Gann]

### Highlights

1. The eutrophication in the Yellow Sea is progressing with various telltale signs of ecosystem change.
2. Extreme warming event in the NE Pacific (2014-2015) is associated with lower chlorophyll a, smaller phytoplankton, and a record toxic algae bloom.

### Basin-wide changes in satellite chlorophyll

To compare mean chlorophyll-a concentrations during the focus period with those of the previous report (PICES 2010), annual mean chlorophyll-a concentrations from MODIS/Aqua were extracted for each 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, average chlorophyll-a concentrations increased while they decreased in the Okhotsk Sea and the eastern Bering Sea (Fig. S-P1). In the Gulf of Alaska and northern California Current region, average chlorophyll-a concentrations increased during 2008-2013. A decrease occurred in most of the western North Pacific with exceptions such as the Yellow Sea and East China Sea.

In 2014-2018, the pattern reversed and in most of the western North Pacific, average chlorophyll-a concentrations increased (Fig. S-P2). In the eastern and northern Bering Sea, they also increased substantially. However, they decreased in the eastern North Pacific, notably in the Gulf of Alaska and California Current region, which may have been related to the 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, chlorophyll-a increased after 2006 but decreased after 2014 (Fig. S-P3). In the eastern Bering Sea, chlorophyll-a decreased after 2006 but increased after 2014. A similar trend can be seen in the Aleutian Islands. In the Gulf of Alaska, chlorophyll-a change did not show a discernable trend because the change was spatially heterogeneous. 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 (Fig. S-P4). In the California Current region, the decrease in chlorophyll-a occurred throughout the year while in the eastern Bering Sea, the changes occurred in the spring and autumn blooms. Similarly, the interannual changes resulted from changes in the seasonal blooms in the PICES regions 15 and 19. On the other hand, in the Gulf of Alaska, seasonal patterns were more or less irregular (Fig. S-P4).

### Expansion of low surface chlorophyll area in the central North Pacific

Low surface chlorophyll-a ( $\leq 0.07 \text{ mg} \cdot \text{m}^{-3}$ ) is a major feature of the central North Pacific from 5°N to 45°N. From 1997-2008, the area of low chlorophyll 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. The expansion of low surface chlorophyll-a waters is consistent with a global warming scenario of increased vertical stratification, but the rates observed already exceed long-term model predictions (Polovina et al. 2008). However, the average chlorophyll-a concentration increased after 2014 (Fig. S-P2).

### The impacts of 2014-16 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 with higher temperatures is evident during the latter part of the 2009-2015 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 2014-16 marine heatwave (often referred to as 'The Blob'). Specifically, the southern California current system saw some of the highest SST and lowest chlorophyll-a minima ever recorded in coastal and transitional areas (Sydeman et al., PICES region 11 chapter). 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 (Fig. S-P5; Zador and Yasumiishi 2019). 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 large size fraction ( $>10 \text{ } \mu\text{m}$ ) chlorophyll-a during 2014 and 2015, suggests fewer large diatom species, thought to be important as a nutritional component in the ecosystem, were present (Fig. S-P6; Siddon and Zador, 2019). Conversely, an increase in diatoms were seen off the coast of British Columbia during the same time period (2009-2015) via the continuous plankton recorder (CPR) data, although reasons remain unclear.

### Wind Mixing and Chlorophyll a

Wind mixing related changes in chlorophyll-a were noted for two separate north Pacific regions (PICES regions 23 and 13). Diminished wind mixing events can be associated with higher 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 southeast Bering Sea PICES region 13 (Fig. S-P7; (Siddon et al., PICES region 13 chapter). However, in the western north Pacific subarctic (PICES region 23), chlorophyll-a had a varied response to deeper MLD via an increase in chlorophyll-a with a deeper MLD over some

areas, and a decrease in chlorophyll-a with a deeper MLD in others (Ono et al., PICES region 23 chapter).

#### Anthropogenic eutrophication in the western North Pacific

The marginal seas in the western North Pacific are under increasing anthropogenic pressures. The Yellow Sea and northern East China Sea receive a large amount of nutrients through air (Chen et al., 2010; Kim et al., 2011), river runoffs (Yuan et al., 2008; Zhou et al., 2010; Li et al., 2015; Wei et al., 2015), and 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 and primary productivity in the Yellow Sea had been steadily increased after 2000 and leveled off in 2008-2011 (Yoo et al., 2019). The Yellow Sea is one ecosystem which has been dominated by anthropogenic pressure, as this pattern is not associated with any climate pattern.

#### Harmful Algal Blooms

An unprecedented bloom of *Pseudo-nitzschia* occurred across the majority of the northeast Pacific coast from the southern California current all the way up to the Gulf of Alaska (GOA) during 2015. The unusual toxic bloom in the GOA coincided with the significant marine warming event (The Blob) covering the same area. Levels of the toxin Domoic Acid were measured in a number of stranded marine mammals, and the event triggered the closure of numerous fisheries along the west coast of the U.S. including razor clam, rock crab and Dungeness crab (McCabe et al. 2016, Zhu et al. 2017). A series of strong spring storms concentrated the toxic diatom *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 progressing 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 N:P ratio in the vicinity of the Changjiang River mouth led to an increase in dinoflagellate blooms. In the Yellow Sea, the frequency of algal blooms had increased between 2000-2010 both in Chinese and Korean coasts. However, the frequency decreased after 2010 (Yoo et al., 2019). The decrease in the frequency of HABs under progressing eutrophication maybe related to the decrease in the water temperature or increased zooplankton and requires further investigation.

#### References

Batten et al., Region 24 chapter

Bograd et al., 2010 NPESR II

Boldt, J.L., Leonard, J., and Chandler, P.C. (Eds.). 2019. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2018. Can. Tech. Rep. Fish. Aquat. Sci. 3314: vii + 248 p.

Chen, H.-Y., Chen, L.-D., Chiang, Z.-Y., Hung, C.-C., Lin, F.-J., Chou, W.-C., Gong, G.-C., Wen, L.-S., 2010. Size fractionation and molecular composition of water-soluble inorganic and organic nitrogen in aerosols of a coastal environment. J. Geophys. Res.: Atmosphere 115 (22), 1–17. <https://doi.org/10.1029/2010JD014157>.

Eisner LB, Gann JC, Ladd C, D. Cieciel K, Mordy CW (2016) Late summer/early fall phytoplankton biomass (chlorophyll a) in the eastern Bering Sea: Spatial and temporal variations and factors affecting chlorophyll a concentrations. Deep Res Part II Top Stud Oceanogr 134:100–114

Kim, T.-W., Lee, K., Najjar, R.G., Jeong, H.-D., Jeong, H.J., 2011. Increasing N abundance in the northwestern pacific ocean due to atmospheric nitrogen deposition. Science 334 (6055), 505–509. <https://doi.org/10.1126/science.12066583>.

Li, H.M., Zhang, C.S., Han, X.R., Shi, X.Y., 2015. Changes in concentrations of oxygen, dissolved nitrogen, phosphate, and silicate in the southern Yellow Sea, 1980–2012: Sources and seaward gradients. Estuar. Coast Shelf Sci. 163, 44–55. <https://doi.org/10.1016/j.ecss.2014.12.013>.

Liu, X., Beusen, A.H.W., Van Beek, L.P.H., Mogollón, J., M., Ran, X., Bouwman, A.F., 2018. Exploring spatiotemporal changes of the Yangtze river (changjiang) nitrogen and phosphorus sources, retention, and export to The east China Sea and Yellow Sea. Water Res. 142, 246–255. <https://doi.org/10.1016/i.watres.2018.06.006>.

McCabe RM, Hickey BM, Kudela RM, Lefebvre KA, Adams NG, Bill BD, Gulland FMD, Thomson RE, Cochlan WP, Trainer VL (2016) An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. Geophys Res Lett 43:10,366–10,376.

Müller, B., Berg, M., Yao, Z.P., Zhang, X.F., Wang, D., Pfluger, A., 2008. How polluted is the Yangtze river? Water quality downstream from the three Gorges dam. Sci. Total Environ. 402 (2–3), 232–247. <https://doi.org/10.1016/j.scitotenv.2008.04.049>.

Ono et al., Region 23 chapter

Polovina, J.J., Howell, E.A., Abecassis, M. 2008. Ocean's least productive waters are expanding. Geophysical Research Letters 35: L03618, doi:10.1029/2007GL031745.

Siddon et al... Region 13 chapter

Siddon, E., and Zador, S., 2018. Ecosystem Status Report 2018: Eastern Bering Sea, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501

Sydeman et al., Region 11 chapter



Tan, E., Wang, G., Moore, W.S., Li, Q., Dai, M., 2018. Shelf-scale submarine groundwater discharge in the northern south China Sea and east China Sea and its geochemical impacts. *J. Geophys. Res. Ocean* 123 (4). <https://doi.org/10.1029/2017JC013405>.

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. *Mar. Chem.* 204 (20), 121–132. <https://doi.org/10.1016/j>.

Yoo et al., Region 20 Chapter

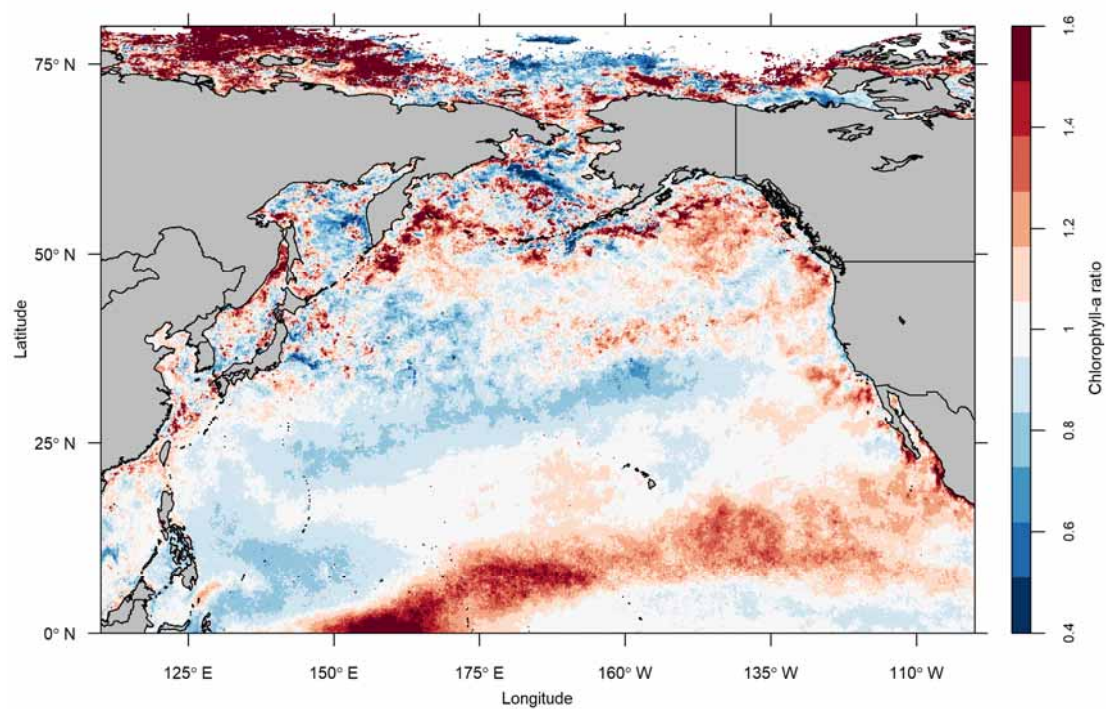
Yuan, D., Zhu, J., Li, C., Hu, D., 2008. Cross-shelf circulation in the Yellow and East China Seas indicated by MODIS satellite observations. *J. Mar. Syst.* 70, 134–149. <https://doi.org/10.1016/j.jmarsys.2007.04.002>.

Zador et al., Region 12 chapter

Zador, S., and Yasumiishi, E., 2018. Ecosystem Status Report 2018: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501

Zhou, F., Huang, D.J., Ni, X.B., Xuan, Q.L., Zhang, J., Zhu, K.X., 2010. Hydrographic analysis on the multi-timescale variability of hypoxia adjacent to the Changjiang River Estuary. *Acta Ecol. Sin.* 30, 4728–4740 (in Chinese with English abstract).

Zhu Z, Qu P, Fu F, Tennenbaum N, Tatters AO, Hutchins DA (2017) Understanding the blob bloom: Warming increases toxicity and abundance of the harmful bloom diatom *Pseudo-nitzschia* in California coastal waters. *Harmful Algae* 67:36–43



## Figures

Fig. S-P3. Ratio of the mean annual chlorophyll-a in 2008-2013 relative to 2003-2007

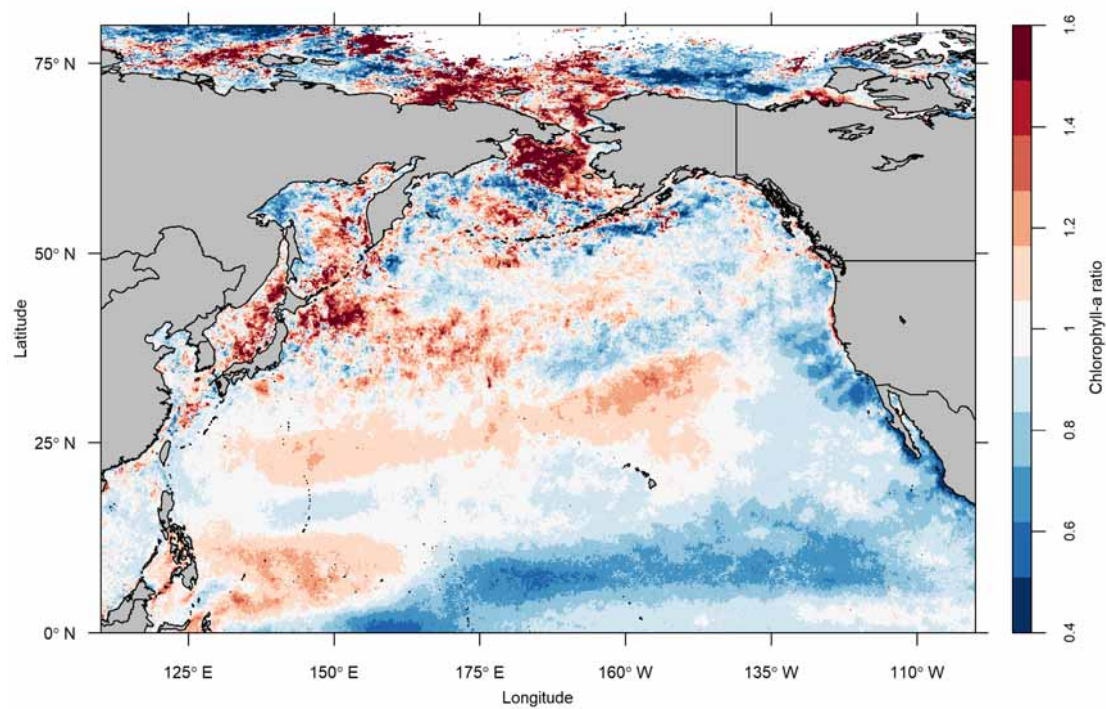


Fig. S-P4. Ratio of the mean annual chlorophyll-a in 2014-2018 relative to 2008-2013

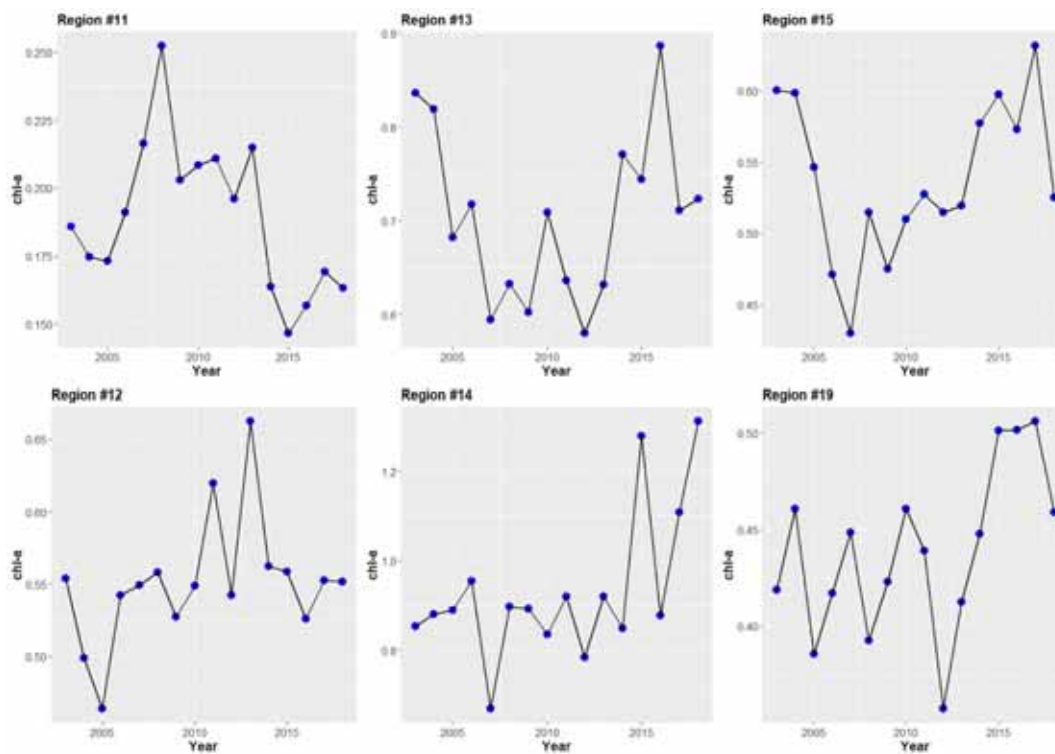


Fig. S-P5. Annual mean chlorophyll-a in regions which showed substantial changes

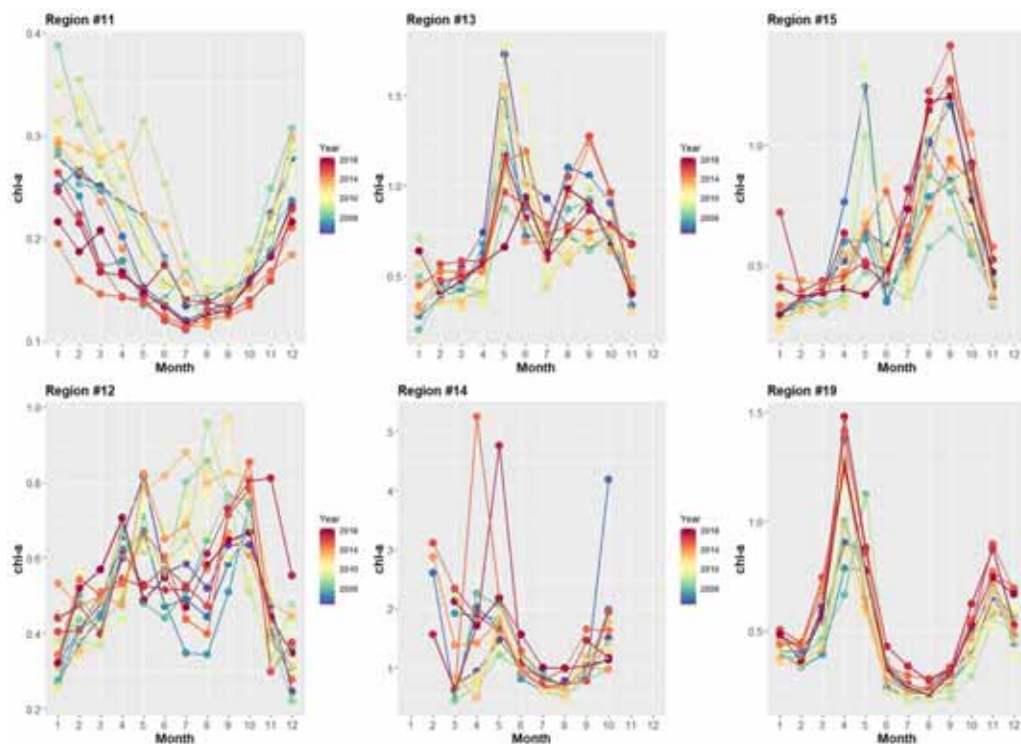


Fig. S-P6. Changes in the seasonal patterns of chlorophyll-a in 2003-2018 period.

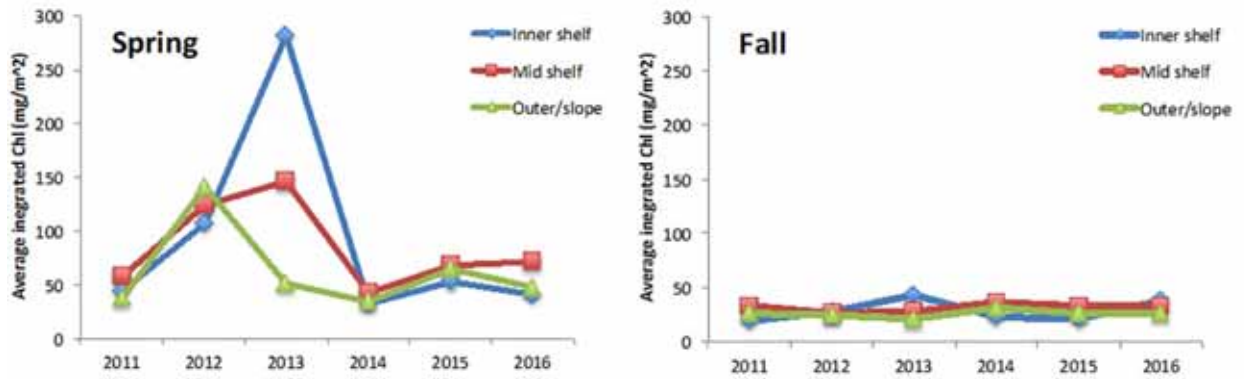


Fig. S-P7. Gulf of Alaska mean values of seasonal integrated chlorophyll-a by shelf zone (inner = GAK1-4; mid= GAK 5-9; outer = GAK 10-13).

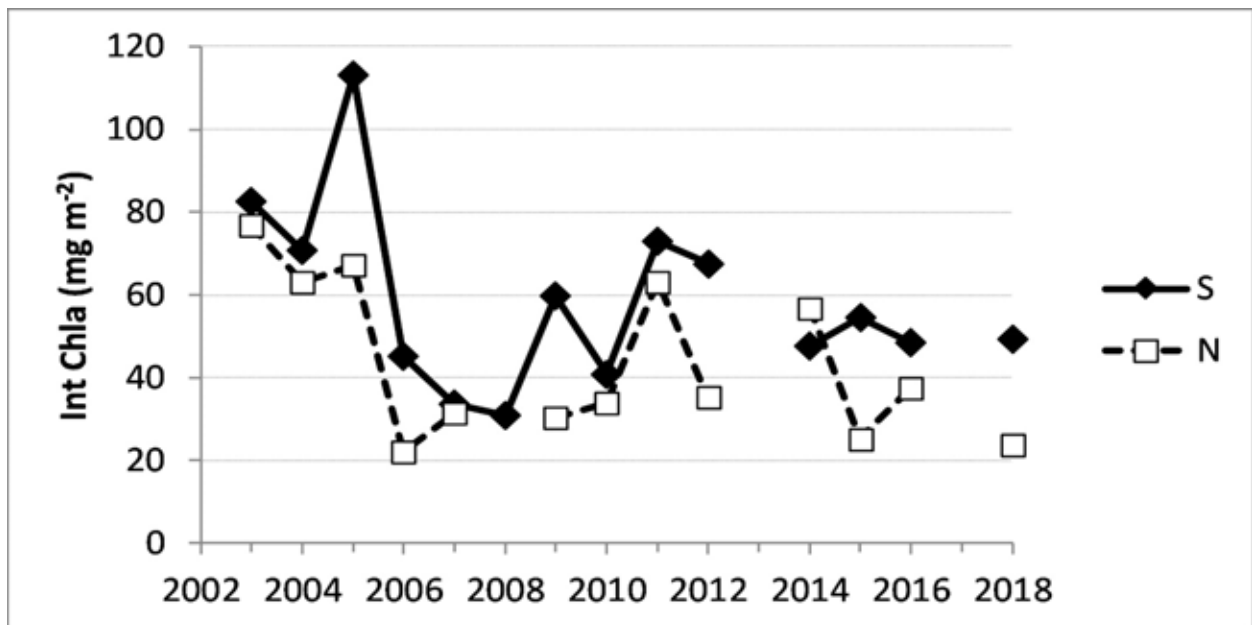


Fig. S-P8. Integrated chlorophyll a (A), and integrated large size fraction chlorophyll-a (>10 um, (B)), over the north and south eastern Bering Sea shelf.

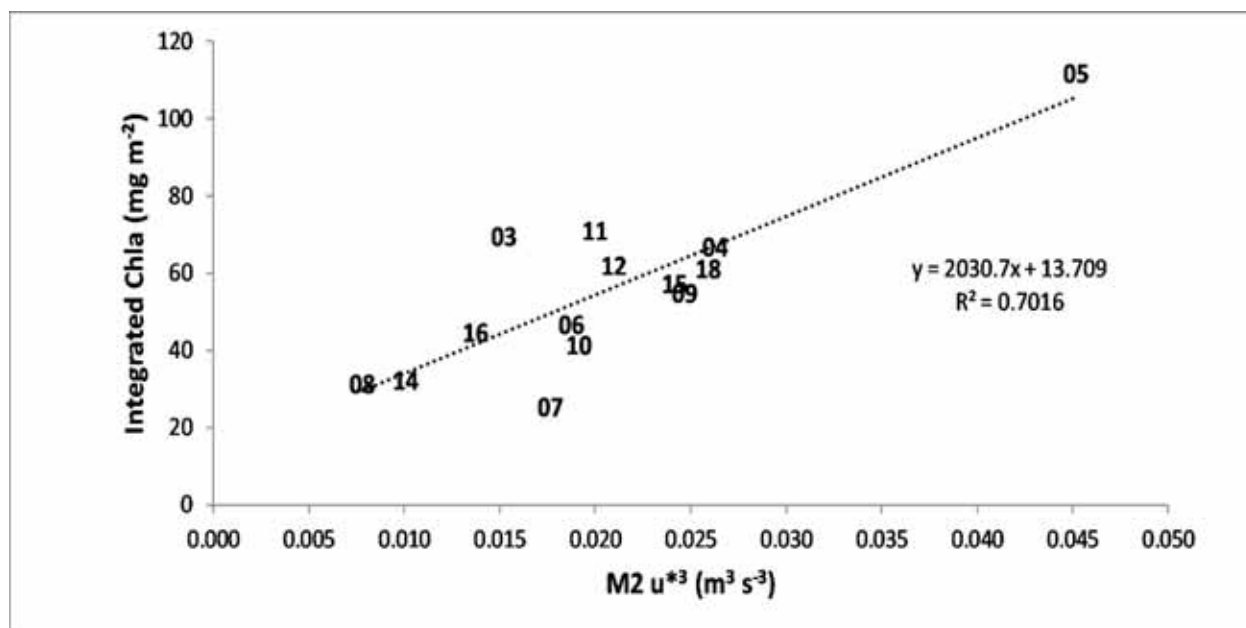


Fig. S-P9. Direct relationship between wind mixing ( $u^3$ ,  $m^3 s^{-3}$ ) and integrated chlorophyll a ( $mg m^2$ ),  $R^2 = 0.70$ .

## Zooplankton [Batten, Tadokoro]

### 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 eastern North Pacific and Bering Sea, but the extraordinary jellyfish blooms noted in the western regions in NPESR2 were absent during this focus period.

### Introduction

Zooplankton are the intermediaries between primary production and higher trophic level fishes, birds and mammals. There are three main size classes of zooplankton which have somewhat different trophic roles and require 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 there are few time series with adequate spatial and/or temporal resolution to understand their dynamics.

The mesozooplankton are those organisms in the size range from about 200  $\mu\text{m}$  to about 1 cm and comprise taxa that spend the entirety of their 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 part of their life cycle. 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 most sampled group and comprise 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 may be over 1 m in diameter. Owing to their larger size and/or greater swimming ability they are challenging to sample so there are also few adequate time series of this group.

Zooplankton sampling methodology and analysis vary by region with differing degrees of taxonomic resolution and units of density. This makes direct comparisons of zooplankton abundance between regions challenging. For the most part, however, during the 2009-2016 focal period interannual variability in total abundance or biomass is much greater than any



observed trend. Where trends are evident they occur as changes to community composition suggesting that diversity is more responsive to forcing than overall density.

The regional chapters of NPESR3 report on 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, during the focal period 2009 to 2016 the synthesis of zooplankton observations across the North Pacific Ocean provide evidence of two processes of note: the expansion of warm water taxa, and changes in the distribution of gelatinous zooplankton.

#### Expansion of warm water taxa

Zooplankton observations for many of the PICES regions reported either an increase in species more typically associated with warmer, southern waters and/or a northwards expansion during the focal period (Figure 1). The significance of this response by the zooplankton community to physical forcing is because the nutritional value of warm water taxa is believed to be poorer. Warm water taxa 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 are less calorific. 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.

The increased abundance of warm water taxa in the northeast Pacific is associated with the marine heatwave of 2014-2016 which produced significantly elevated SSTs from California to Alaska. Several time series in the California Current system (PICES region 11) report mesozooplankton changes; positive anomalies in southern copepods from spring 2014 along the Newport Line (Figure xx2) and in 2014-2016 off Vancouver Island (Figure xx3), a shift to smaller copepod taxa from 2013-2015 on the southern British Columbia shelf (mean copepod size from CPR data, Figure xx4). In the Alaska Current system (PICES region 12) negative anomalies in mean copepod size also occurred from 2013-2016 on the western Gulf of Alaska shelf (Figure xx5 and Batten et al., 2018). The oceanic NE Pacific showed similar patterns with positive anomalies of southern copepod taxa and southern chaetognath taxa from 2014 to 2016 observed at offshore Line P stations suggesting the marine heatwave caused a simultaneous basin-wide change in zooplankton community composition with a higher proportion of southern, typically smaller, taxa.

In the Bering Sea regions, particularly the wide shelf in PICES region 13, the impacts of warm ocean conditions on the zooplankton community are reflected as changes in the relative abundance of taxa rather than appearance/disappearance of warm/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-medium sized copepods

and euphausiids while the former favours smaller copepod species that benefit from the warmer waters (Hunt et al., 2011).

Although the 2014-16 marine heatwave event is not considered to have had a direct influence in the western subarctic gyre there have been significant increases in SST over much of the region (Figure xx6). A northwards 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 (Figure xx7). In the Oyashio region the zooplankton communities identified as “warm” and “transition” expanded northwards in 2015 and 2016; years that ocean conditions were also warm with increased 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 Continuous Plankton Recorder and so some PICES regions have limited information. However, other surveys do assess gelatinous plankton routinely. Both groups have been surveyed in the northeastern Pacific (Regions 11,12 and 24) and in the eastern Bering Sea (PICES region 13). Cnidaria was the main group surveyed in the western North Pacific (Regions 19 and 20), especially for assessing abundance of giant jelly fish (e.g. *Nemopilema nomurai*).

In the eastern North Pacific the pattern of year to year variation of the gelatinous zooplankton biomass is different from north to south. Thaliacea and Cnidaria had low biomass from 2000 to the mid-2000s off Baja California (Figure xx8), followed by an increase and sustained high values until the early 2010s. After that, the biomass decreased through the focal period. Conversely, the biomass of the Cnidaria 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 increased biomass was evident during the remainder of the focal period.

In the eastern Bering Sea (PICES region 13), although different species showed differing patterns, overall biomass generally showed 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, for example the increased temperatures (Table xx1) may be responsible.

In the western North Pacific, the biomass of the giant jellyfish *N. nomurai* showed low values in 2000-2001 but then it increased and high values were maintained until 2009 in the coastal waters of Japan (PICES region 20). These large jellyfish blooms were thus a significant phenomenon in the NPESR2 (McKinnel et al., 2010) and further information can be found in

Uye and Brodeur (2017). However, during much of the 2009-2016 focal period 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 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 the western Yellow Sea (PICES region 20). In the Oyashio waters (PICES region 18), Thaliacea had high biomass in 2013-2016 which were years with warm ocean temperatures.

## References

- Batten, S.D., Raitos, D.E., Danielson, S., Hopcroft, R.R., Coyle, K. and McQuatters-Gollop, A. (2018). Interannual variability in lower trophic levels on the Alaskan Shelf. *Deep Sea Research II*. 147, 58-68.
- Hunt, G. L., Coyle, K. O., Eisner, L. B., Farley, E. V., Heintz, R. A., Mueter, F., Napp, J. M., Overland, J. E., Ressler, P. H., Salo, S., and Stabeno, P. J. (2011). Climate impacts on eastern Bering Sea foodwebs: a synthesis of new data and an assessment of the Oscillating Control Hypothesis. *ICES Journal of Marine Science*, 68: 1230–1243.
- Kawahara, M., Uye, S., Ohtsu, K. and Iizumi, H. (2006). Unusual population explosion of the giant jellyfish, *Nemopilema nomurai*, (Scyphozoa: Rhizostomae) in east Asian waters. *Mar. Ecol. Prog. Ser.* 307: 161–173.
- McKinnell, S.M., Batten, S., Bograd, S.J., Boldt, J.L., Bond, N., Chiba, S., Dagg, M.J., Foreman, M.G.G., Hunt Jr., G.L., Irvine, J.R., Katugin, O.N., Lobanov, V., Mackas, D.L., Mundy, P., Radchenko, V., Ro, Y.J., Sugisaki, H., Whitney, F.A., Yatsu, A., Yoo, S. (2010). Status and trends of the North Pacific Ocean, 2003-2008, pp. 1-55 In S.M. McKinnell and M. J. Dagg. [Eds.] *Marine Ecosystems of the North Pacific Ocean, 2003-2008*. PICES Special Publication 4, 393 p.
- Uye, S.I. and Brodeur, R.D. (Eds.) (2017). Report of Working Group 26 on Jellyfish Blooms around the North Pacific Rim: Causes and Consequences. PICES Sci. Rep. No. 51, 221 pp.

## Figures

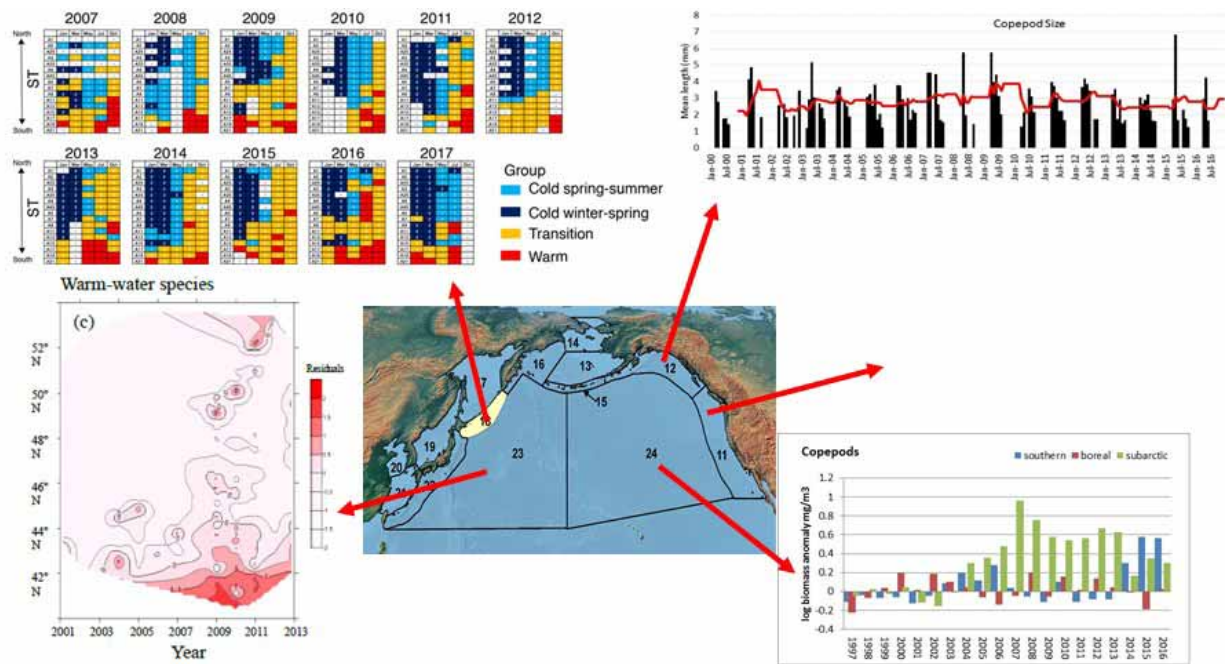


Figure . Anomalies of warm water species abundance for PICES regions 11, 12, 18, 23 and 24

Tables

Region	Region 11				Region 12				Region 18				Region 23				Region 24			
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Region 11	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Region 12	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Region 18	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Region 23	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Region 24	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Table 1. Summary of gelatinous zooplankton trends in each region from 2000 to 2018. The red and blue cells indicate increasing and decreasing levels, respectively.

## Fishes and Invertebrates [Baker]

### Introduction

Across the North Pacific, fish populations have shown shifts in distribution in response to broad-scale changes in ocean temperatures. Dynamics of fish species utilizing 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). Mechanistic understanding of fish responses to climate variability is vital for evaluating past and forward projections of environmental forcing. Individual species show differential responses, but commonalities among functional groups enables pan-Pacific comparison of fishes responses to ecosystem shifts during the focal time period

Two main trends for fishes and invertebrates apparent in the 2009-2016 focus period are latitudinal shifts in distribution and cyclical or phase shifts in species composition. The Kuroshio-Oyashio system and the California Current include large latitudinal contrast of environments. In these areas, biomass patterns and commercial catches in these small pelagic fishes indicate decadal changes 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 profound impacts on dynamics of fish community composition and species dominance, particularly among small pelagic species. Distinct temperature regimes are also evident in most systems in this timeframe, superimposed on an increase in temperatures generally. This has caused shifts in distribution and in some cases abundance. The northernmost part of the North Pacific (PICES regions 13 - 16), the Bering Sea and Aleutian Islands 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 eastern subarctic (PICES region 11 and 12), a largescale and extensive marine heatwave was observed in 2014 and 2015 and altered fish and invertebrate dynamics along the western Pacific.

Trends in fish and invertebrate biomass may be indicative of trends in pelagic or benthic production or response to variability in the overall marine environment. Catch biomass also indicates trends in exploited resources over time. Many of the datasets in this section borrow from data collected as surveys and assessments or from commercial catch data.

### Forage Fish

Exemplar forage fish species within the North Pacific include sardine (*Sardinops* spp.), anchovy (*Engraulis* spp.), herring (*Clupea pallasii*), and capelin (*Mallotus villosus*). 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 with

differential interactions, demonstrating drivers of population dynamics vary from western to eastern Pacific systems.

The Kuroshio Current system (PICES region 22) provides spawning and nursery grounds for several forage fish species, including Japanese sardine (*Sardinops melanostictus*), Japanese anchovy (*Engraulis japonicus*), round herring (*Etrumeus teres*), mackerel (*Scomber* spp.), and Pacific saury (*Cololabis saira*). Out-of-phase population oscillations occur in this region between sardine and anchovy. Broadly, during PDO-positive phases, ocean water temperatures are cooler and sardine populations dominate the community composition. During PDO-negative phases, water temperatures are warmer and anchovy dominate.

Since the late 1980s, sardine have experienced very low population levels, whereas anchovy, jack mackerel, and common squid have experienced relatively high population levels. Recently, however, sardine populations have started to increase, showing a sign of their population recovery. In contrast, the population levels of anchovy, jack mackerel, and common squid are now declining simultaneously. 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 of species alternations (Kazuaki ref?).

In the eastern Bering Sea, climate variability has impacted the spatial extent of seasonal sea ice, leading to changes in community composition (e.g., zooplankton, fish) and trophic dynamics. Two key forage fish species in the system are capelin (*Mallotus villosus*) and Pacific herring (*Clupea pallasii*). The biomass of both species is greater in the northern areas, but shifts in distribution and abundance occur in response to above- and below-thermal conditions (i.e., warm and cold years). 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. 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 NBS shelf (Andrews et al., 2016).

In the focus time period (2009-2015), the shelf area of the eastern Bering Sea experienced a shift from cold to warm conditions with the transition occurring around 2013. During the cold years, capelin biomass was high, especially in the north, with a strong decline after 2015. Simultaneously, herring biomass was higher in the northern areas, demonstrating a similar range contraction as the previous cold stanza. Concurrently, in the Gulf of Alaska, capelin abundance increased sharply in 2007, then decreased in 2014 and 2015. The increase in abundance coincides with cooler years, consistent with patterns observed in the eastern Bering Sea and abundance decreased with the emergence of the marine heatwave.

Both sardine and anchovy were present in the California Current ecosystem (PICES region 11) 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. In the mid 2000s, sardine decreased and anchovy increased, which was related to the environment (i.e., upwelling) in 2000-2002 (positive for anchovy) and 2003-2005 (negative for anchovy). The decline in sardine was largely due to fishing. After 2009, abundance declined for both species. The central stock of northern anchovy (*Engraulis mordax*) grew from a collapsed state in the early 1950s, demonstrated two periods of relative stability at different levels from 1967 through 2004 that was followed by another short-term spike of abundance in 2005–2006, then collapsed again and remained low from 2009 through 2015.

Figure 1. Exemplar forage species for the Kuroshio Current System, Eastern Bering Sea (SBS+NBS), and the California Current Ecosystem.

### Groundfish

In the Gulf of Alaska (PICES region 12) total log(CPUE) for groundfish decreased from its highest value in 2013 to its lowest value in 2017. There was no significant long-term trend over time from 1993 to 2017 in either the eastern or western regions, but total CPUE decreased significantly and by more than 50% between 2013 to 2017 in both regions. The drop in CPUE since 2013 was widespread among species with over two-thirds of the species in both regions showing declines. Large declines were observed in arrowtooth flounder, walleye pollock, and Pacific ocean perch in both regions; northern rockfish, grenadiers, rock sole and Atka mackerel in the western Gulf of Alaska; and shortraker rockfish, spiny dogfish, Pacific halibut, Dover sole, and dusky rockfish in the eastern Gulf of Alaska.

Apex predator biomass, already low in 2013 and 2015, declined steeply in 2017 with the diminishing biomass of Pacific cod, arrowtooth flounder, and halibut. The marine heatwave appeared to cause high natural mortality for cod.

The distribution of rockfish species in the bottom trawl surveys appears to have stabilized for the Gulf of Alaska. The stability of the distribution indicates that each of the species occupy a fairly specific depth distribution. As temperatures rise and fall around the mean, the depth distribution does not change, indicating that rockfish are not changing their habitat or distribution to maintain a constant temperature.

Based on analysis of rockfish from 14 bottom trawl surveys in the Gulf of Alaska and Aleutian Islands (Rooper 2008), five species assemblages were defined based on similarities in their distributions along geographical position, depth, and temperature gradients. The 180 m and 275 m depth contours delineated major divisions between assemblages inhabiting the shelf, shelf break, and lower continental slope. Divisions between species were also seen geographically with some centered in southeastern Alaska and others in the northern Gulf of Alaska and Aleutian Islands.



There are several statistically significant trends observed from recent surveys. The distribution of adult rougheye rockfish, adult Pacific Ocean perch and shortraker rockfish have been shallower in the most recent surveys of the Aleutian Islands (Figure Rooper1). The mean-weighted distribution of Northern rockfish have shown a significant trend towards the western Aleutians (although recently the trend has been flat). Changes in depth and spatial distributions for adult rougheye rockfish, shortraker rockfish, northern rockfish and adult Pacific Ocean perch in the observed in the Aleutian Islands are probably related to changes (increases) in overall abundance. Walleye Pollock, an important ecological and commercial fish species in the northwestern Pacific Ocean were exposed to warm ocean conditions during the 2009-2016 focus time period that were favorable for recruitment of strong year classes of Pollock.

There were no significant temporal trends in mean-weighted temperature distributions, varying less than about 1°C for all species. Increases in mean-weighted temperature have been observed in 2016 as ocean temperatures increased and may trend higher if temperatures remain high.

### Salmonids

Salmon production in the North Pacific is at an all-time high (NCEAS 2018). Increasing temperature coupled with increasingly extreme variability in environmental conditions year to year have had impacts on stock dynamic and life history patterns. Both the PDO and 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, Ruggerone). 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. In the coastal waters of Japan (2007–2016), the catch of coho in 2011 was 14000 metric tonnes, while the annual catch of each of the other four Pacific salmon species was ca. 0–80 metric tonnes. Sockeye salmon decreased from 2.9 million in 1992 to ca. 0.2 million in 2013–2015 (NPAFC 2017).

Salmon are increasingly threatened at the southern end of their range, while expanding in the north and into the Arctic. Shifts in life history are also evident. In the Gulf of Alaska abundance indices in 2014-2015 over-forecast adult returns due to higher mortality in the first summer at sea as juveniles experienced extreme elevated sea temperatures and reduced prey resources.

Annual catch of masu increased abruptly to 0.47–0.82 thousand metric tonnes during 2007–2011. Masu salmon have been identified as an important predator of chum juveniles.

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 marine heatwave 2014-16. It appears trends of Asian and American salmon stocks are different. Physical processes regulating the heat budget of the upper water layer seem to be the major drivers of Pacific salmon productivity in the North Pacific Ocean.

In the Gulf of Alaska, strong biennial trends in salmon cycles are evident, with high runs in 2013 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 survey were low and decreasing throughout this time interval and returns of adult Chinook and coho salmon have been in decline

In the eastern Pacific, trends in the estimated abundance of juvenile salmon indicated a recent increase in the productivity of Pacific salmon in the eastern Bering Sea (PICES region 13) and increased presence in the northern Bering Sea (PICES region 14). Juvenile sockeye were the most abundant species followed pink, chum, and Chinook salmon in the eastern Bering Sea and pink and chum in the northern Bering Sea. 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. The center of gravity of distributions indicated that juvenile Chinook, chum, and pink salmon were farther south during warm years, while juvenile sockeye salmon were distributed farther north and west in warm years. Higher abundances of juvenile salmon during recent warm years indicate improved environmental conditions for the survival in the eastern Bering Sea during summer and/or in freshwater rivers and lakes of western Alaska.

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).

#### Chum

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 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), chum salmon catches have decreased since 2010 and pink salmon catch 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 recorded 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). In the western Bering Sea stock abundance and catch of chum salmon increased during early 2000s, reaching a maximum in 2014.

#### Pink

The catch of pink salmon in Japan was predominant in even-numbered years compared with odd-numbered years during the 1990s and early 2000s.. Fluctuations in pink salmon abundance mirrored climatic changes. Cold ocean winter conditions in 2012-2013 resulted in decrease in overwinter survival and reduced catch in 2013 and 2014. Warm ocean conditions of El Nino 2015 were associated with an increase of survival and higher catch of pink salmon in 2016 (Kotenev et al., 2015).

Pink salmon originating from the eastern Kamchatka Peninsula are the primary pink salmon stock in the central Bering Sea (PICES region 15) and central subarctic North Pacific Ocean (PICES region 23 and 24) (Takagi et al. 1981, Myers et al. 1996). 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 across the Pacific Rim, reached records abundances (650 million fish) in 2009 and 2011, approximately 70% of all Pacific salmon. Evidence indicates pink salmon affect zooplankton abundance, which in turn affects phytoplankton abundance (Batten et al. 2018); growth, age, and survival of other species of salmon (Ruggerone et al. 2016, Ruggerone and Connors 2015), and diet and reproduction of seabirds (Springer and van Vliet 2014). There is growing evidence that pink salmon may have influenced the decline in length-at age, survival and abundance of Chinook salmon.

#### Sockeye

Sockeye salmon stocks in 2009-2016 on the eastern coast of Kamchatka were relatively high and increased in a linear manner over this time interval. Sockeye salmon are spending less time in freshwater and more time in the ocean, leading to larger adults on return but no change in mean age (Schindler and Ohlberger). The effects of North Pacific anomalous warming in the eastern North Pacific also appear to have effects on salmon.

Juvenile sockeye salmon responded to warming with an expansion in their range and distribution farther north. 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.

#### Chinook

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

### Squids, krill, jellies, and mesopelagic fishes

In the western Pacific (PICES region 22), Japanese common squid (*Todarodes pacificus*), have experienced relatively high abundance for several decades, however, are now declining as part of an apparent regime shift in the pelagic community. In the Oyashio (PICES region 18) there have been considerable variation in landings. In the western Bering Sea (PICES region 16), squid *Boreoteuthis borealis* had substantial increase of biomass in 2003-2009. In the California Current PICES region 11, market squid (*Doryteuthis opalescens*) and krill (euphausiids) were at fairly high abundance levels in most areas. Both mature and immature squids (*Boreoteuthis borealis*, *Gonatus Kamschaticus*, *Engraulis japonicus*, *Todarodes pacificus*, *Onychoteuthis borealijaponica*) are transported from the North Pacific Ocean to the Bering Sea with high abundance of early life stages in the western Bering Sea and Aleutian Islands (Glebov et al., 2010a; Glebov et al., 2010b).

The total biomass of mesopelagic fish in the North Pacific is uncertain but they represent an important species group and numerically dominate fish assemblages in many regions (Irigoin et al. 2014). Oceanic species occur abundantly on the offshore side of the Kuroshio, while pseudo-oceanic species, adapting to certain habitats of continental slopes, slopes of islands, and seamounts, occur dominantly on the onshore side (Ohshima et al. 2012; Sassa et al. 2004; Sassa and Konishi 2015). While there is substantial interannual variability and decadal-scale trends Watanabe and Kawaguchi (2003), these myctophids and mesopelagic species show an increasing trend after 2000, possibly related to the increasing trend in water temperature in the Kuroshio region. Jellies in the western Bering and Aleutian Islands decreased more than six-fold between 2003-2009 (800 kg km<sup>-2</sup>) and 2010-2015 (125 kg km<sup>-2</sup>). Salps and other colonial pelagic organisms were noted in high abundance in the Gulf of Alaska in 2014-2015, during the marine heatwave.

### Crabs

Historical trends of commercial crab biomass and abundance are highly variable 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. In the northern Bering Sea St. Matthew blue king crab continued declines to the lowest levels observed for this stock. Most declines are in the eastern stocks while western stocks have been increasing or stable in recent years. In the Yellow Sea (PICES region 20), species composition of annual commercial catch suggests the fish and invertebrate community structure has changed sequentially with a distinct period 1999-2014, matching reported regime shifts in the North Pacific by past studies (Hare and Mantua, 2000; Jung, 2014). In the same time period the biomass of flower crabs (*Portunus pelagicus*), blue crab (*Portunus trituberculatus*) increased in contrast to depressed populations of flatfish benthivores.

Among commercial crabs in the Sea of Okhotsk the most abundant species in the last decade have been snow crabs (*Chionoecetes opilio*, *Chionoecetes bairdi*) and red king crabs (*Lithodes aequispinus*, *Paralithodes camtschaticus*, *Paralithodes platypus*). 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 crab stocks remain extremely depressed, possibly due to negative trends in benthic production or a negative benthic response to environmental variability. Pelagic red crabs (*Pleuroncodes planipes*) in the California Current appear to be increasingly since 2015.

### Tunas and sharks

Large pelagic predators such as skipjack tuna (*Katsuwonus pelamis*), blue shark (*Prionace glauca*), and neon flying squid (*Ommastrephes bartramii*) are important predators in the lower latitudes and oceanic regions of the North Pacific. In the Aleutian Islands, piscivorous apex predators make up the largest proportion in the Eastern Aleutian biomass, decreasing towards the Western Aleutians.

### References

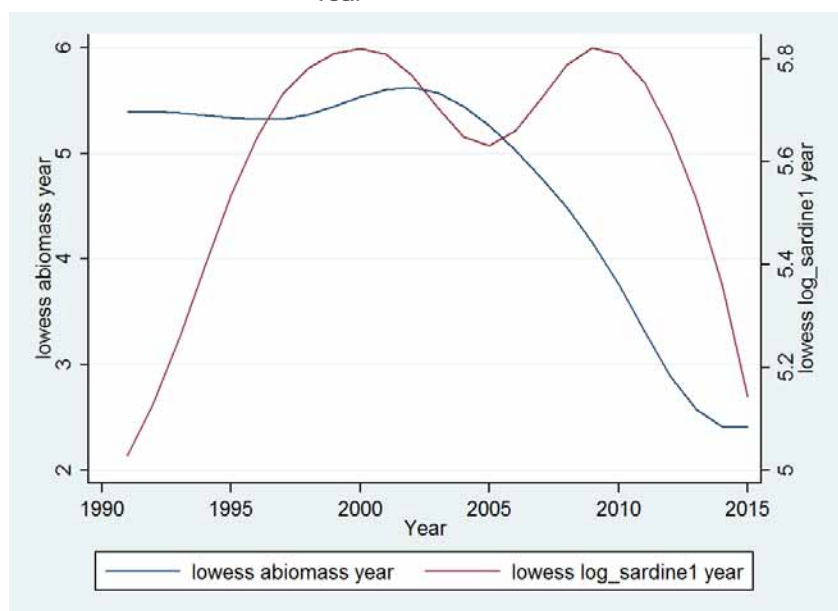
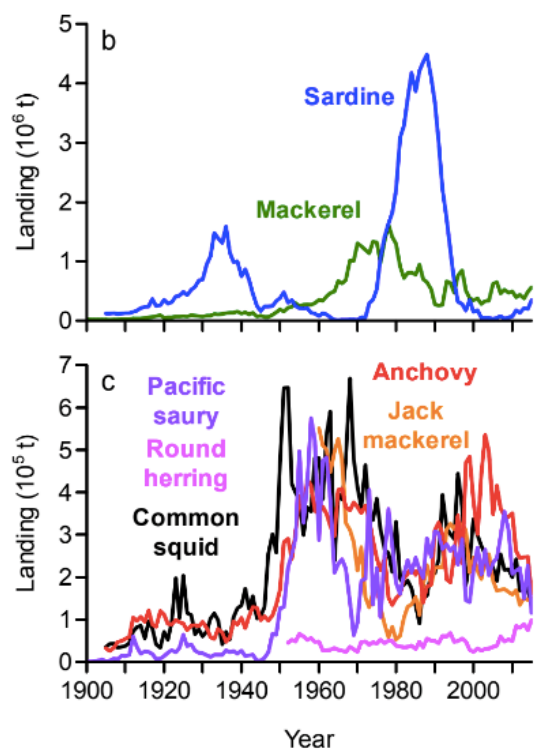
Robert Foy, Christie Lang, Jon Richar Kodiak Laboratory, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, Kodiak, AK

Urawa, S., T. D. Beacham, M. Fukuwaka, and M. Kaeriyama. 2018. Ocean ecology of chum salmon. In R. Beamish (ed.) Ocean Ecology of Pacific Salmon and Trout. American Fisheries Society, Bethesda, Maryland, pp.161-317.

Report of the Proceedings for the International year of the SALmon Workshop toward effective coupling of the science of a changing climate with salmon and people. National Center for Ecological Analysis and Synthesis 2018.

### Figures

Figure 1. Exemplar forage species for the Kuroshio Current System, Eastern Bering Sea (SBS+NBS), and the California Current Ecosystem. (this information will be redrawn as a single ticker-tape figure with 2 species per Region (Kuroshio: sardine and anchovy; EBS: capelin and herring; CC: sardine and anchovy)).



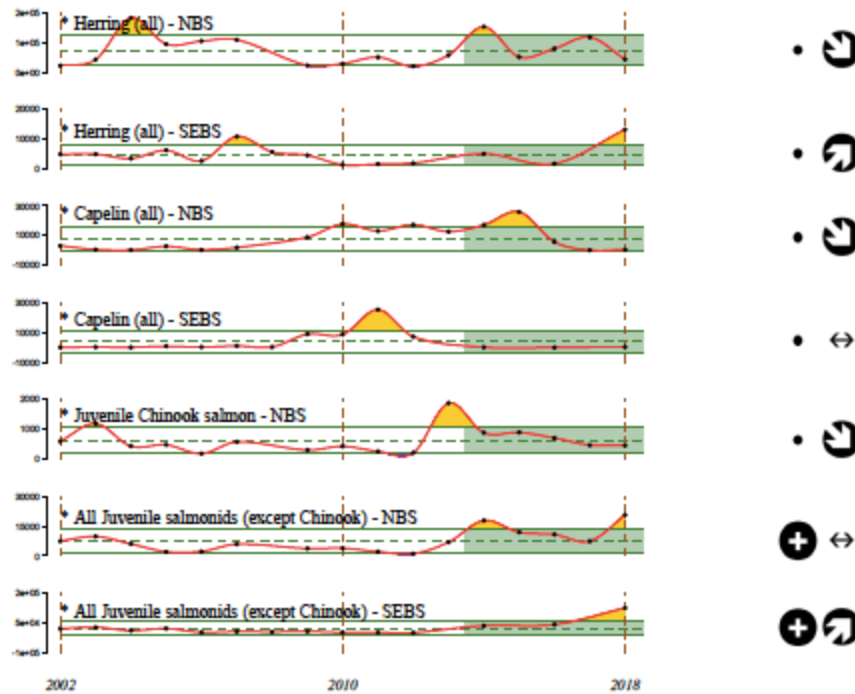
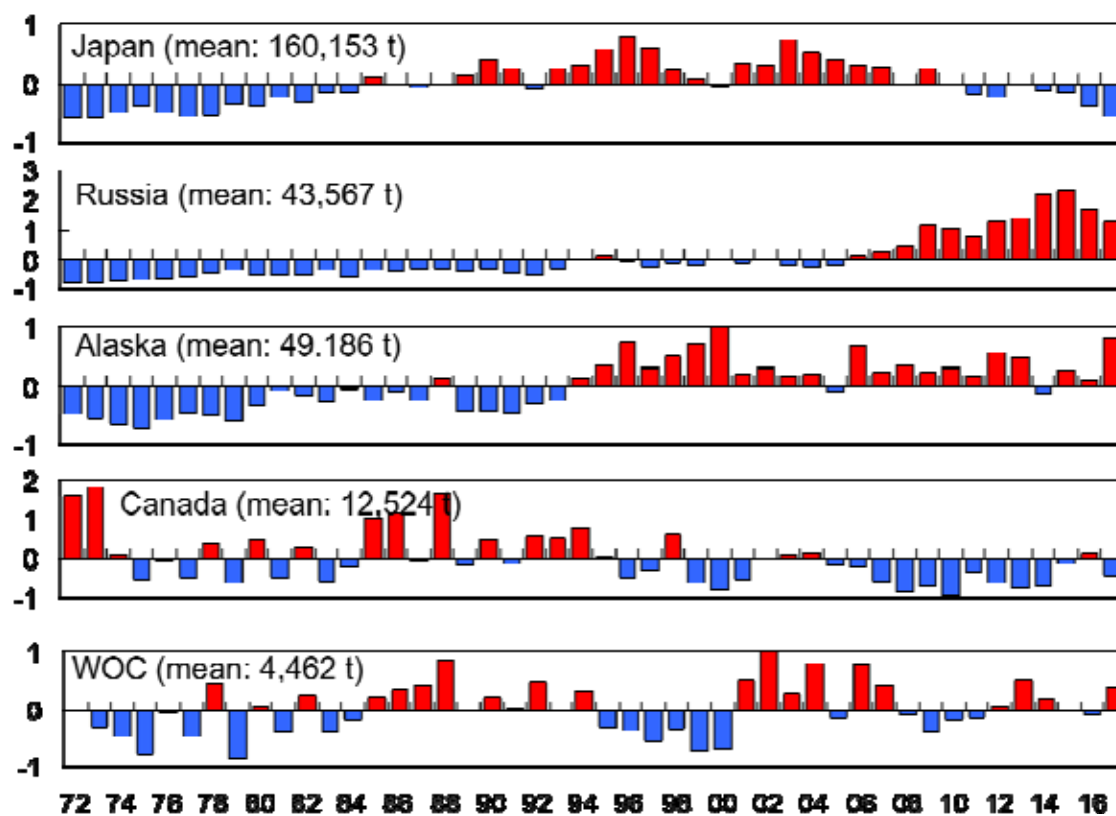


Figure 2. Chum salmon catch (weight in metric tonnes) anomalies by region, 1972-2017 [Urawa et al. 2018; Dr. Shigehiko Urawa (Hokkaido National Fisheries Research Institute, Fisheries Research and Education Agency, Japan)].





## Marine Birds and Mammals [Zador, Ortiz, Sydeman]

### Highlight

Warm water events in the Eastern North 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.

### Introduction

The North Pacific is home to a diverse group of seabird and marine 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). Seabirds and marine mammals spend most of their time at sea, foraging primarily on fish and invertebrates (e.g., squids and zooplankton). Most seabird breeding colonies or pinniped 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, seabirds 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 may have discrete calving areas, young typically travel with their mothers, and thus parents are not restricted to central place foraging.

Seabirds 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). Seabirds can also be grouped by whether they are primarily surface or near-surface foragers (e.g. kittiwakes *Rissa sp.*) or divers (e.g. puffins *Fratercula sp.*). Like seabirds, marine mammals 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 regional reports (Table 1).

### Seabird Populations and Productivity

Large scale changes in North Pacific seabird populations are not well known within the focal period of 2009-2014. For some species, there has been recovery from historic hunting or eggging, 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, twelve seabird species in the North Pacific are of current conservation concern, although local conservation status can vary among and within PICES regions. (Table 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 range northward in California, Velarde et al. 2015; PICES region 11 report). 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 eggging, such as with murre 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 seabird productivity (i.e., the number of young produced per female per year) for many locations across the North Pacific. In general, seabird breeding success exhibited high variability during the focal period. Many breeding failures occurred from 2014 through 2016 across the North Pacific. This poor productivity was related to reduced food resources associated with the development and persistence of the 2014-2016 NE Pacific marine heatwave (Yang et al. 2018).

Large-scale seabird 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 murre during winter 2015/2016 (Piatt et al. submitted). Mortalities have been substantial, with 100,000s affected. In almost all cases, starvation has been implicated, demonstrating extreme food shortages. Because seabirds 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.

#### Pinniped Populations and Productivity

Population trends for pinnipeds show substantial regional variation. For example, during the 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). Numbers are increasing and near or at carrying capacity in the eastern Gulf of Alaska and increasing in the western Pacific at the Kuril Islands, Sakhalin, and northern Okhotsk. A notable "superabundance" was recorded in Cape Soya (Hokkaido Island). In the central north Pacific, colony size is stable in the central Aleutians and Kamchatka, 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, 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, during a survey in the western North Pacific (PICES region 23), the number of Sei, Bryde's, and Minke whales appeared to have decreased. 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, with more frequent sightings over longer periods each year. For example, humpback whales are increasing along the California Current (PICES region 11 report), have possibly reaching carrying capacity in SE Alaska (PICES region 12 report), and expanded northward into the Arctic. The overall recovery of whales is still partial, and several remain listed as endangered by the IUCN (Table 2).

Recovered or recovering large cetaceans may be driving 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 2000's, 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.

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 has been linked with the abrupt reduction in humpback whale reproductive output. The heatwave has also been linked to an unusual mortality event from 2015-2016 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 between 2013 and 2016 (PICES region 11).

### References

Ainley, D.G. and Lewis, T.J., 1974. The history of Farallon Island marine bird populations, 1854-1972. *The Condor*, 76(4), pp.432-446.

Bond, N.A., Cronin, M.F., Freeland, H., and Mantua, N. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophys. Res. Lett.* 42: 3414-3420. doi:10.1002/2015GL063306

Gabriele, C. and Neilson, J., 2018. Continued Decline of Humpback Whale Calving in Glacier Bay and Icy Strait. In: Zador, S., and Yasumiishi, E., 2018. Ecosystem Status Report 2018: Gulf of Alaska, Stock Assessment and Fishery Evaluation Report, North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501.

Gaston, A. J. and J. M. Hipfner (2000). Thick-billed Murre (*Uria lomvia*), version 2.0. In *The Birds of North America* (A. F. Poole and F. B. Gill, Editors). Cornell Lab of Ornithology, Ithaca, NY, USA. <https://doi.org/10.2173/bna.497>

Gibble, C., Duerr, R., Bodenstein, B. Lindquist, K., Lindsey, J., Beck, J., Henkel, L., Roletto, J., Harvey, J, Kudela, R. 2018. Investigation of a largescale Common Murre (*Uria aalga*)

Jones, T, Parrish, J K, Peterson, WT, Bjorkstedt, EP, Bond, NA, Ballance, LT, Bowes, V, Hipfner, MJ, Burgess, HK, Dolliver, JE, Lindquist, K, Lindsey, J, Nevins, HM, Robertson, RR, Roletto, J, Wilson, L, Joyce, T, Harvey, J. 2018. Massive mortality of a planktivorous seabird in response to amarine heatwave. *Geophysical Research Letters*, 453:193–3202.

Naves, L.C. 2015. Alaska Subsistence Harvest of Birds and Eggs, 2014, Alaska Migratory Bird Co-Management Council. Alaska Department of Fish and Game Division of Subsistence, Technical Paper 415, Anchorage.

NPFMC 2017, Northern fur seals: Synthesis Paper for the NPFMC, October 2017

Piatt, J. (common murre massive mortality reference).

Yang, B., Emerson, S.R., Peña, M.A. 2018. The effect of the 2013-2016 high temperature anomaly in the subarctic Northeast Pacific (the “Blob”) on the net community production. *Biogeosciences*, 15:6747-6759.

Zador, S.G., Punt, A.E. and Parrish, J.K., 2008. Population impacts of endangered short-tailed albatross bycatch in the Alaskan trawl fishery. *Biological Conservation*, 141(3), pp.872-882.

## Tables

Table 1. Seabird and marine mammal data in regional NPESR3 reports. PICES regions are listed by number.

<b>Seabirds - Alcids</b>		<b>Seabirds - Procellarids</b>	
Auklets	11, 12, 14, 15, 18	Albatross	11
Murrelets	11, 15	Petrels	11
Murres	12, 14, 15, 18,	Shearwaters	11, 20
Puffins	12, 15, 18	Storm Petrels	12, 15, 20
Guillemots	15, 18	<b>Seabirds - Gulls</b>	
<b>Seabirds - Cormorants</b>		Terns	11
Cormorants	15, 18	Gulls	11, 15, 18, 20
		Kittiwakes	12, 15
<b>Marine Mammals - Pinnipeds</b>		<b>Marine Mammals - Baleen whales</b>	
Sea lions	11, 12, 15, 18	Rorquals	11, 12, 14, 23
seals	15, 18, 20	Bowhead	14
fur seals	13		

Table 2. IUCN redlist of marine birds and mammals of the PICES regions of the North Pacific (IUCN 2019). 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	2009	2019	As of	Change	Region
<b>Marine birds</b>						
Short-tailed albatross	<i>Phoebastria albatrus</i>	VU	VU	07.08.18	↑	Oceanic North Pacific
Laysan albatross	<i>P. immutabilis</i>	VU	NT	07.08.18	—	Oceanic North Pacific
Black-footed albatross	<i>P. nigripes</i>	EN	NT	07.08.18	↑	Oceanic Pacific
Ashy storm-petrel	<i>Hydrobates homochroa</i>	EN	EN	07.08.18	↓	California Current System
Long-billed murrelet	<i>Brachyramphus perdix</i>	NT	NT	10.08.18	↓	Sea of Okhotsk
Kittlitz's murrelet	<i>B. brevirostris</i>	CR	NT	07.08.18	↓	Alaska to Sea of Okhotsk
Marbled murrelet	<i>B. marmoratus</i>	EN	EN	07.08.18	↓	Gulf of Alaska, Aleutians
Craveri's murrelet	<i>Synthliboramphus craveri</i>	VU	VU	07.08.18	↓	S. California Current
Guadalupe murrelet	<i>S. hypoleucus</i>	*	EN	07.08.18	↓	S. California Current
Scripp's murrelet	<i>S. scrippsi</i>	*	VU	07.08.18	↓	S. California Current



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Japanese murrelet	<i>S. wumizusume</i>	V U	V U	07.08.1 8	↓	Kuroshio and Oyashio
Steller's eider	<i>Polysticta stelleri</i>	V U	V U	07.08.1 8	↓	Bering Sea, Arctic Ocean
<b>Marine mammals</b>						
Steller sea lion	<i>Eumetopias jubatus</i>	EN	N T	04.02.1 6	↑	Coastal North Pacific
Sei whale	<i>Balaenoptera borealis</i>	EN	E N	25.06.1 8	↑	World Oceans
Blue whale	<i>B. musculus</i>	EN	E N	16.03.1 8	↑	World Oceans
Fin whale	<i>B. physalus</i>	EN	V U	04.02.1 8	↑	World Oceans
North Pacific right whale	<i>Eubalaena japonica</i>	EN	E N	19.12.1 7	?	Northern North Pacific, Bering Sea
North Pacific right whale	<i>Eubalaena japonica</i>	CR	C R	18.12.1 7	?	Northeast Pacific subpopulation
Bowhead whale	<i>Balaena mysticetus</i>	EN	E N	07.03.1 8	↓	Sea of Okhotsk subpopulation
Grey whale	<i>Eschrichtius robustus</i>	CR		Possibly extinct		Western North Pacific subpopulation
Beluga whale	<i>Delphinapterus leucas</i>	CR	C R	22.06.1 7	↓	Cook Inlet, Gulf of Alaska
*previously listed together as <i>S. hypoleucus</i> assessed separately 2014						

Option 2 for Table 1, showing species, diet type, and regions)

<b>Seabirds - Alcids</b>		<b>Procellarids</b>	
Plank Cassin's auklets	11	inverts Black footed albatross	11
mixed Parakeet auklets	12, 14, 15	mixed Cook's petrel	11
plank Crested auklets 14, 15	14, 15	pisc Pink-footed shearwater	11
plank Least auklets 14, 15	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	11	<b>Seabirds - Gulls</b>	
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
<b>Seabirds - Cormorants</b>		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		
<b>Marine Mammals - Pinnipeds</b>		<b>Marine Mammals - Baleen Whales</b>	
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



## Human Dimensions [Criddle]

### Highlights

1. From 2000 to 2017 economic growth rates in PICES nations exceeded the global mean; population growth rates were below the global mean.
2. Since 2000 the catch by PICES nations of diadromous fish, marine fish, and crustaceans have increased slightly, while there has been a steady decline in the catch of molluscs.
3. There has been a substantial increases in aquaculture production of freshwater fish, diadromous fish, marine fish, crustaceans, molluscs, and aquatic plants
4. 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.

### Introduction

The status and trends of human dimensions of the North Pacific 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, etc. The North Pacific is among the most important fishery regions in the world, and the six PICES member nations are world leaders in freshwater and marine fisheries and aquaculture. Wild fisheries are important to the PICES member nations, 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 et al. 2020). Between 2000 and 2017, the average catch from the North Pacific represented 23.4% of the global catch and, on average, the six PICES nations produced 37% of the global supply of fish from aquaculture and wild fisheries (Criddle et al. 2020). Similarly, the North Pacific yielded 41% and 35% of the global catches of crustaceans and molluscs and PICES nations produced 52% and 75% of the global supply of crustaceans and molluscs (Criddle et al. 2020).

In 2000, the human population of PICES member nations totaled 1.9 billion people, 31.3% of the global population (United Nations Basic Statistics, 2020). By 2017, the human population of PICES member nations exceeded 2.1 billion people, but only represented 28% of the global population. That is, population growth in PICES 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 the Russian Federation (-19.5 thousand people per year). By itself, China accounts for 67.3% of the population of the PICES member nations. From 2000 to 2017, among PICES member nations, 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, the Republic of Korea, and the Russian Federation are also among the top 12 global economies (United Nations Basic Statistics, 2020). Together, the six PICES member nations generated \$23.2 trillion in the gross domestic product (GDP), 48.2% of the global economy in 2000; in 2017, the GDP of PICES member nations was \$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 the production of seafood, 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 nations exceeds the global average, it might be anticipated that the demand for seafood in PICES member nations 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, the production of aquatic products by PICES member nations, and the consumption of aquatic products within PICES member nations is presented below. Additional details are included in Criddle et al. (2020).

### Wild Fisheries

Annual observations (2000-2017) of the total catch of fish, crustaceans, and molluscs, from the North Pacific are shown in Figure 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 1. Overall trends include slight increases for catches of crustaceans (7,992 t/year), diadromous fish (9,342 t/year), and marine fish (126,012 t/year). However, the increases in crustaceans and diadromous fish are not statistically significant (Table 2). The total catch of molluscs from the North Pacific has declined by a statistically significant average of 52,190 t/year over this 18-year (2000-2017) period (Table 2).

From 2000 to 2017, over 87% of the annual mean North Pacific catch of diadromous fish (primarily Pacific salmon) was harvested by three PICES member nations: the USA (37.4% of total), Russia (28.6% of total), and Japan (21.3% of total). (See Table 1 and Figure 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 fishermen and a statistically significant increase (4.87% per year) in the share of diadromous fish caught by Russian fishermen (Table 2). The shares of North Pacific diadromous fish caught by Canada and China have declined, but the declines are not statistically significant (Table 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 2).

On average, catches by China between 2000 and 2017 account for over 50% of all catches of marine fish from the North Pacific (Table 1, Figure 1b). China's share of marine fish catch has increased at an average (statistically significant) rate of slightly more than 1% per year (Table 2). Together, Japan, the USA, and Russia harvest a little over 40% of all marine fish from the North Pacific (Table 1, Figure 1b). From 2000 to 2017, the shares of the North Pacific 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 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 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 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 1, Figure 1c). Japan's share of the North Pacific crustacean catch has declined by almost 5% per year (Table 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 2).

China, Japan, and Korea account for over 95% of the North Pacific mollusc catch (Table 1, Figure 1d). Over the past 18 years, North Pacific mollusc harvests by Canada, China, Japan, and Korea have declined at statistically significant rates (Table 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 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 2). The increase in Russian catch of crustaceans from the North Pacific has been substantial (1,193 t/year), as is the observed change in USA catch of crustaceans (2,180 t/year) (Table 2). The observed trend in the USA catch of fish from the North Pacific is also statistically significant and substantial (25,961 t/year); however, the increase is not statistically significant when fish catch is disaggregated to diadromous fish and marine fish categories (Table 2).

In contrast, trends in Japanese and Canadian catches from the North Pacific are negative (Table 2). In the case of Japan, these declines are statistically significant and substantial. In the 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 nations 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 nations and the ROW are shown in Figure 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 nations and the ROW are reported in Table 3. Together, the PICES member nations produce 59% of the global aquaculture supply of fish, 53% of the global aquaculture supply of crustaceans, 87% of the global aquaculture supply of mollusks, and 72% of the global aquaculture supply of aquatic plants (Table 3). Most of this production occurs in China (Figures 2a-f). Although aquaculture production increased at a statistically 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 (see NPESR3 section on Human Dimensions).

### Combined Wild Fisheries and Aquaculture

The global supply of marine fish from wild harvests and aquaculture was relatively constant from 2000 through 2017. In contrast, there were substantial increases in the total production of freshwater fish in China (0.784 million t/year) and ROW (1.189 million t/year), and substantial increases in ROW production of diadromous fish (0.181 million t/year). The net effect of these trends in fisheries and pisciculture is that the global supply of fish increased by about 34 million t 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 nations and the ROW rely on catches from the North Pacific is represented as a share of wild fisheries in Table 5 and as a share of the total supply from aquaculture and wild fisheries in Table 6. 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 percent. Finfish fisheries of Japan, the Russian Federation, the USA, and PICES as a whole, have also become increasingly reliant on the North Pacific. In contrast, the Republic of Korea's finfish fisheries have become less reliant on the North Pacific. Crustacean fisheries of the North Pacific have become less important to Canada, China, and the Republic of Korea, and more important to Japan, the Russian Federation, and the USA, although those trends are not statistically significant in the cases of Canada, the Republic of Korea, and the Russian Federation. The importance of North Pacific mollusk fisheries has declined for Canada and China and increased for the remaining members of PICES (see NPESR3 section on Human Dimensions).

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 6). Canada, Japan, the Russian Federation, 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, the Republic of Korea, and PICES as a whole have become less dependent on North Pacific catch as a component of their supply of marine fish (Table 8). For crustaceans and mollusks, 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, the Russian Federation, and the USA (see NPESR3 section on Human Dimensions).

### Consumption of Aquatic Products

Per capita annual consumption of aquatic products (kg/person/year) for PICES member nations and the ROW for 2000-2013, are shown in Figure 3. Between 2000 and 2013, Japanese per capita consumption of aquatic products declined by 13.1kg for fish, 2.2kg for crustaceans, 4.1kg

for mollusks, and 0.6kg 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 mollusks, and -0.042 kg/year for aquatic plants. Over this same period, per capita annual consumption of fish has also declined in Canada (-0.128kg/year), the Republic of Korea (-0.310kg/year), and the USA (-0.178kg/year). In contrast, per capita annual consumption of fish increased in China (0.565kg/year) and the Russian Federation (0.470kg/year). Per capita annual consumption of crustaceans increased in every nation except Japan. Per capita annual consumption of mollusks increased in China, the Republic of Korea, and the Russian Federation, while decreasing Canada, Japan, and the USA. From 2000-2013, the average per capita annual consumption of aquatic plants increased in China, and the Republic of Korea but decreased in Japan (data not available for Canada, USA, and the Russian Federation). It is noteworthy that Korean per capita annual consumption of aquatic plants increased by 16.2kg between 2000 and 2013.

## References

- Criddle, K.R., et al. 2020. Status and Trends of Human Dimensions in the North Pacific Ecosystem. Chapter XX in P. Chandler et al. (editors) North Pacific Ecosystem Status Report, The North Pacific Marine Science Organization (PICES), Sidney, British Columbia, Canada
- UN FAO Fish Stats. 2020. <http://www.fao.org/fishery/topic/16140/en>. Accessed in January 2020.
- United Nations Basic Statistics. 2020. <https://unstats.un.org/unsd/snaama/Basic>. Accessed in January 2020.

## Tables

	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	928,822	16,332,006	17,260,828	2,463,154	2,449,048	7,985
Non-PICES nations	86	706,959	707,045	46,293	31,213	-
Total	928,908	17,038,965	17,967,873	2,509,448	2,480,261	7,985

Table 1. Annual mean (2000-2017) total catch of fish (t), crustaceans (t), and molluscs (t), and take of marine mammals (number) from the North Pacific. (Source: UN FAO Fish Stats)

	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%*

Table 2. Mean annual percent change (2000-2017) in the catch (t) or take (number) from the North Pacific. \* denotes values that are statistically significant at a 5% level. (Derived from UN FAO Fish Stats)

	Diadromous Freshwater				Aquatic		
	Fish	Fish	Marine Fish	All Fish	Crustaceans	Mollusks	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	20,616,521	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	3,663,769	30,146,706	1,834,907	35,645,382	4,945,860	13,377,624	20,046,783

Table 3. Annual mean (2000-2017) total aquaculture production (t) by PICES member nations and all other nations (ROW). (Source: UN FAO Fish Stats)

	Diadromous Fish	Marine Fish	All Fish	Crustaceans	Mollusks	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%

Table 5. Mean annual (2000-2017) percent of the national and global catch taken from the North Pacific by PICES member nations and ROW. (Derived from UN FAO Fish Stats)

	Diadromous Fish	Marine Fish	All Fish	Crustaceans	Mollusks
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%
Republic of Korea	47.44%	62.55%	61.98%	70.70%	38.24%
Russian Federation	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%

Table 6. Mean annual (2000-2017) North Pacific catch as a percent of total production by PICES members and all other nations (ROW). (Derived from UN FAO Fish Stats)

## Figures

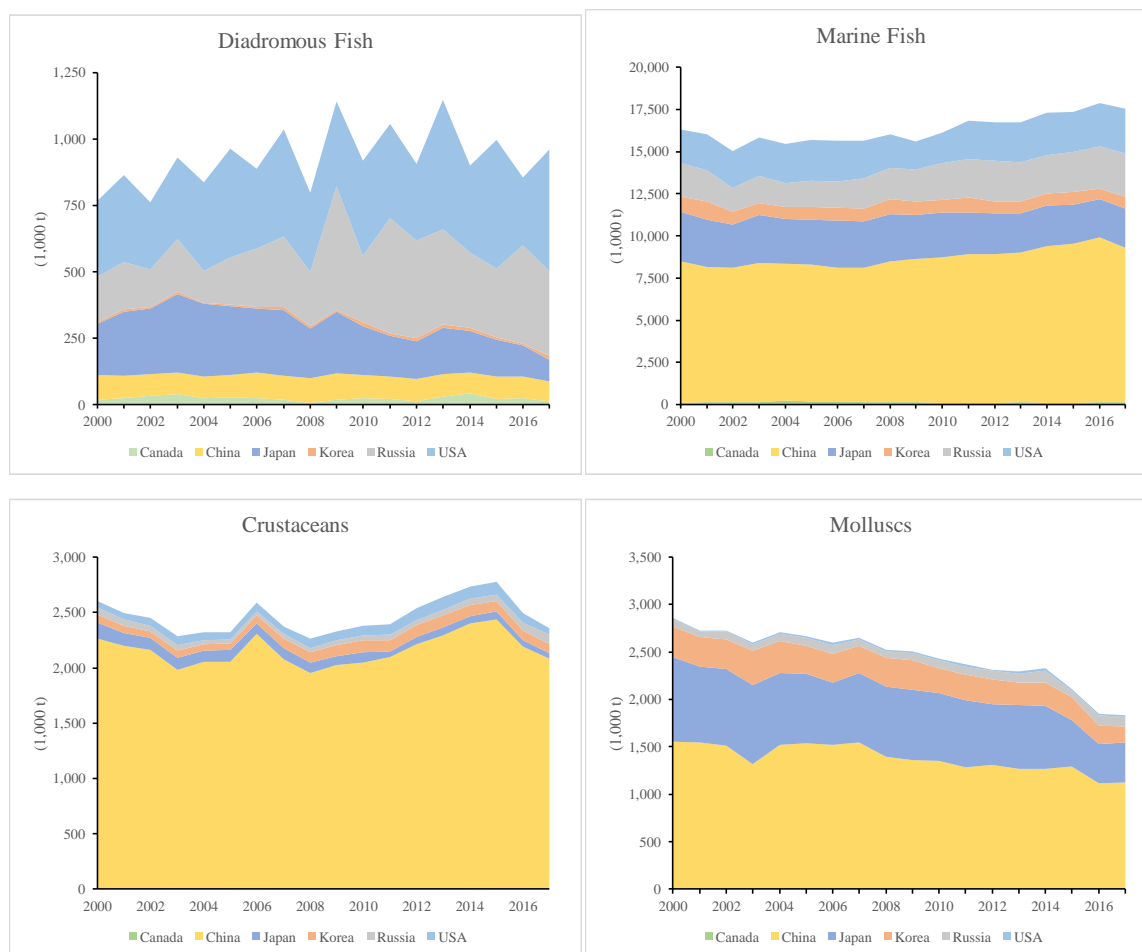


Figure 1a-d. Annual catch of fish (t), crustaceans (t), and molluscs (t) from the North Pacific), 2000-2017.

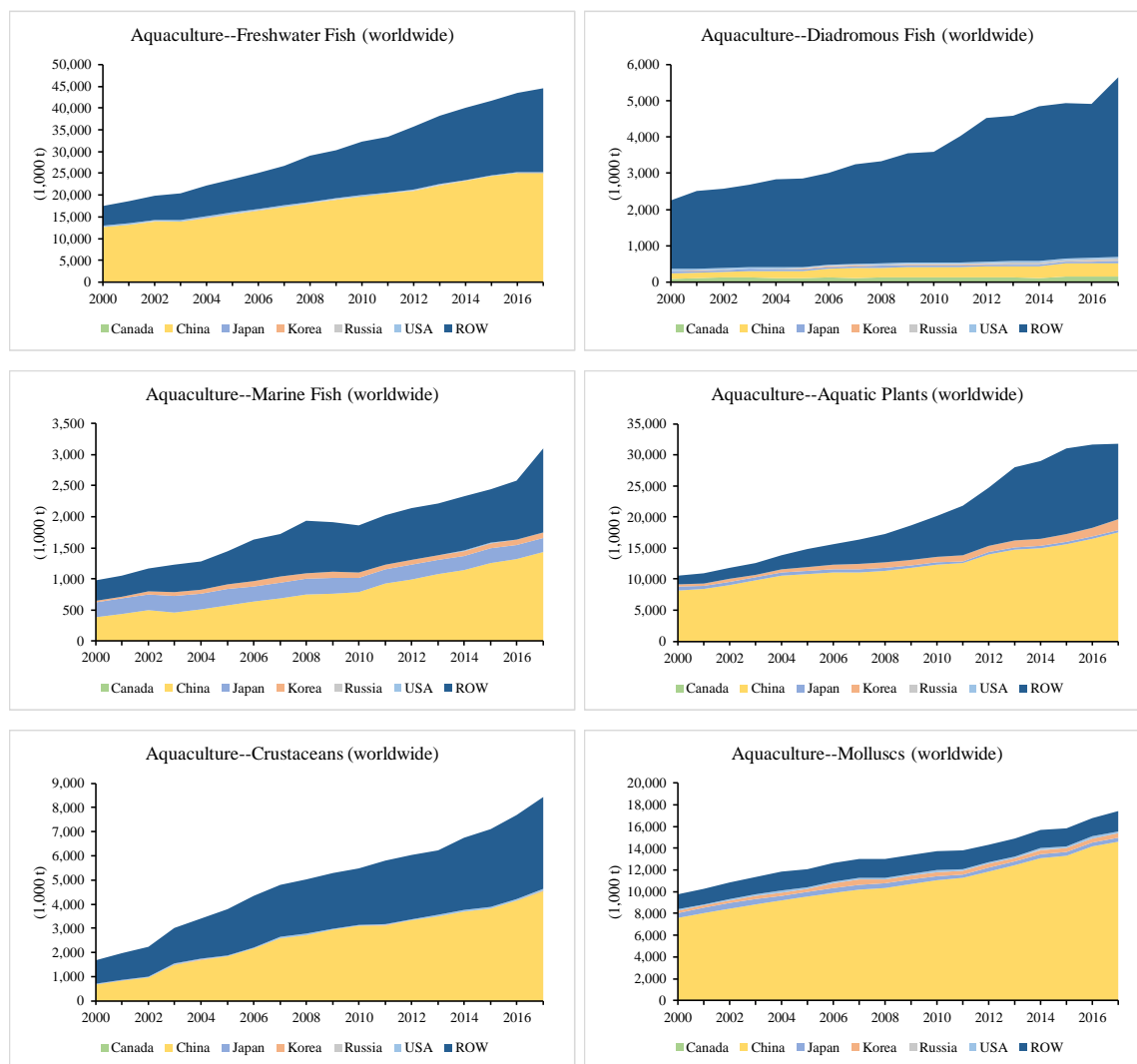


Figure 2a-f. Annual production from aquaculture: fish (t), crustaceans (t), mollusks (t), and aquatic plants (t), 2000-2017. (Source: UN FAO Fish Stats <http://www.fao.org/fishery/topic/16140/en>.)



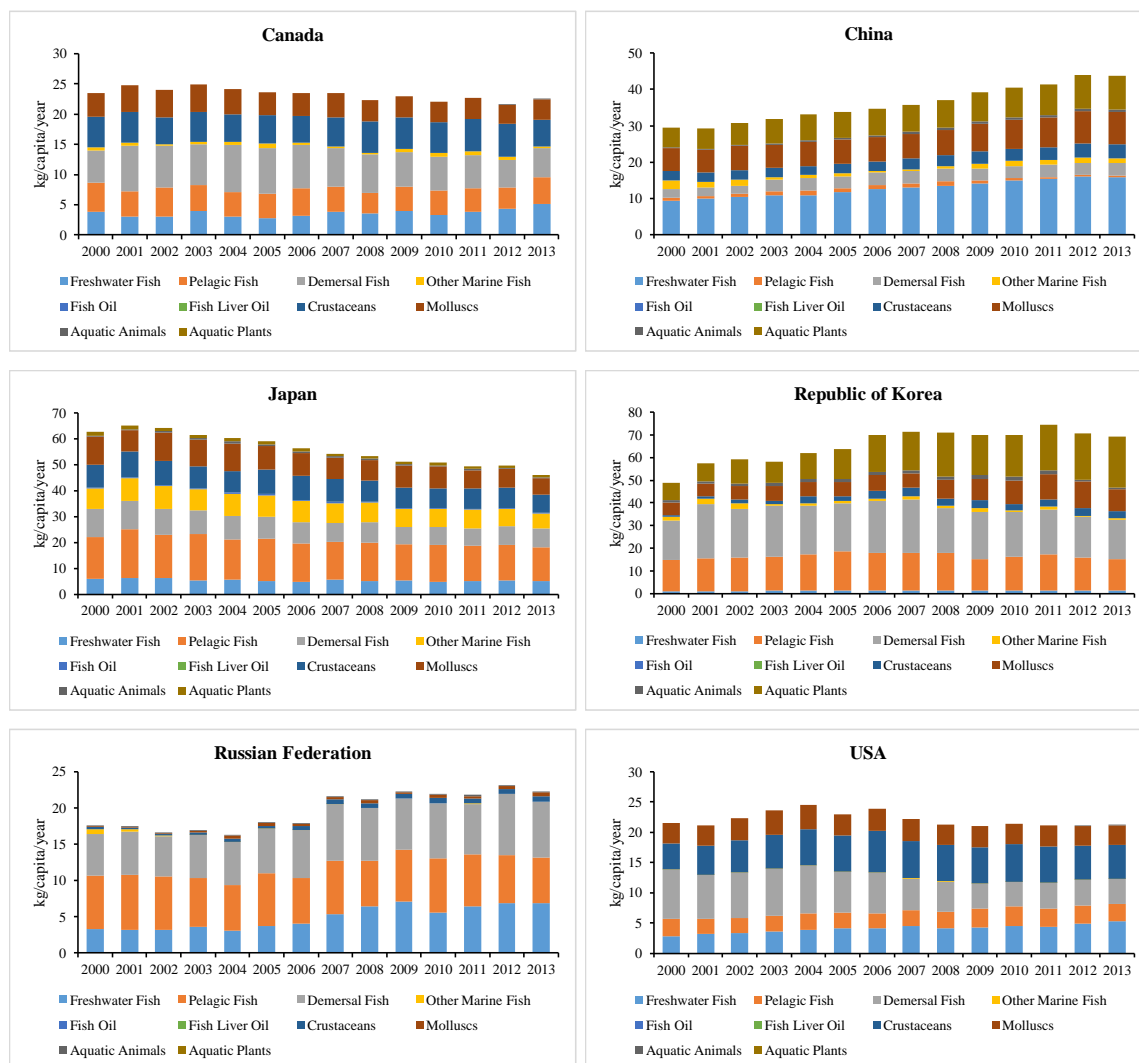


Figure 3a-f. Per capita annual consumption of aquatic products (kg/person/year), 2000-2013. (Source: UN FAO Fish Stats <http://www.fao.org/fishery/statistics/global-consumption/en>)

Breakout Box 1 Marine Heatwaves

Breakout Box 2 Marine Debris in the North Pacific Ocean

Breakout Box 3 Eutrophication in the Yellow Sea