Exxon Valdez Oil Spill
Long-Term Monitoring Program (Gulf Watch Alaska) Final Report

Continuous Plankton Recorder monitoring of plankton populations on the Alaskan Shelf

Exxon Valdez Oil Spill Trustee Council Project 21120114-D
Final Report

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Study History: The first Continuous Plankton Recorder project supported by the *Exxon Valdez* Oil Spill Trustee Council (02624-BAA) was built on a large-scale plankton sampling program that was initially funded by the North Pacific Marine Research Initiative in 2000 and 2001. Recognizing the relevance to the planned Gulf Ecosystem Monitoring program, the *Exxon Valdez* Oil Spill Trustee Council awarded one year of funding for two transects in 2002, one north-south and one east-west across the Gulf of Alaska. The North Pacific Research Board then provided funding for the east-west transect from 2003. Funding for the north-south transect was continued through the *Exxon Valdez* Oil Spill Trustee Council Gulf Ecosystem Monitoring program for four more years (until 2008) via projects 030624 and 040624. After the Gulf Ecosystem Monitoring program ended, the value of the plankton data to herring restoration efforts was acknowledged with an additional year of funding as Restoration Project 070624 and, subsequently, as a contract under the Integrated Herring Research Program for three years (2010-2012), project 12100624. At about this time, a funding consortium for the North Pacific Continuous Plankton Recorder survey was established under the auspices of PICES (the North Pacific Marine Science Organization), so that several agencies (including the North Pacific Research Board and Department of Fisheries and Oceans, Canada) contributed to the survey's costs and reducing the amount requested from the *Exxon Valdez* Oil Spill Trustee Council. From 2012, the Continuous Plankton Recorder project became part of the Long-Term Monitoring Program of the *Exxon Valdez* Oil Spill Trustee Council (Gulf Watch Alaska) with four years of funding under Restoration Project 16120114-A, from 2013-2016. In 2017 this current contract was awarded for five years, under Restoration Project 21120114-D. Annual reports have been submitted for each year of this contract, and data have contributed to the National Oceanographic and Atmospheric Administration's ecosystem status reports annually. We have continued to work closely with Herring Research and Monitoring and the Gulf Watch Alaska principal investigators throughout this contract, with a number of papers resulting from these collaborations (Batten et al. 2016, 2019, 2022, Litzow et al. 2020, Arimitsu et al. 2021, Hoover et al. 2021, Pinchuk et al. 2021, Suryan et al. 2021).

Abstract: The Continuous Plankton Recorder transect samples the Alaskan shelf from lower Cook Inlet across the slope into the open Gulf of Alaska, providing a record of taxonomically resolved, seasonal, near-surface zooplankton and large phytoplankton abundance over a wide spatial scale. Sampling takes place approximately monthly, six times per year, usually between April and September. Outputs from the project include indices of plankton abundance (e.g., large diatom abundances, estimated zooplankton biomass), seasonal cycles (phenology of key groups), and community composition (e.g., appearance of warm water species, change in dominance by

some groups). Variability in any, or all, of these indices might be expected to flow-through to higher trophic levels such as herring, salmon, birds, and mammals that forage across the region. Recent results show that interannual variability in plankton dynamics is high and plankton responded clearly and rapidly to the recent warm conditions, with changes evident in abundance, composition, and timing.

Key words: Alaskan Shelf, fisheries, food webs, heatwave, phenology, phytoplankton, plankton, productivity, trophic levels, warming, zooplankton

Project Data: Data exist as abundances per sample for over 400 zooplankton and phytoplankton taxonomic entities together with sample location, time, and date of collection (with position reported as the mid-point of each 18.5 km sample). Data from over 1,000 processed samples from 2017 to 2021 (and > 5,000 samples from previous years) have been collected, and specific data requests are available from Clare Ostle, email claost@mba.ac.uk. 2021 data are still being analyzed and going through quality control processes.

All data and metadata from 2017-2020 surveys (plankton counts and physical data) are available on the Gulf of Alaska data portal and published with DataONE at the links below:

> https://gulf-of-alaska.portal.aoos.org/#metadata/87f56b09-2c7d-4373-944e-94de748b6d4b/project/folder_metadata/2638347
>
> https://gulf-of-alaska.portal.aoos.org/#metadata/87f56b09-2c7d-4373-944e-94de748b6d4b/project/folder_metadata/2510313
>
> https://search.dataone.org/view/10.24431/rw1k21a

Data from 2021 will be posted at these links when completed.

The data custodian is Carol Janzen, Director of Operations and Development, Alaska Ocean Observing System, 1007 W. 3rd Ave. #100, Anchorage, AK 99501, 907-644-6703. janzen@aoos.org.

Data are archived by Axiom Data Science, a Tetra Tech Company, 1016 W. 6th Ave., Anchorage, AK 99501.

Citation:

Ostle, C., and S. Batten. 2023. Continuous Plankton Recorder monitoring of plankton populations on the Alaskan Shelf. *Exxon Valdez* Oil Spill Long-term Monitoring Program (Gulf Watch Alaska) Final Report (*Exxon Valdez* Oil Spill Trustee Council Project 21120114-D), *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

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Continuous Plankton Recorder monitoring of plankton populations on the Alaskan Shelf

EXECUTIVE SUMMARY

The *Exxon Valdez* Oil Spill Trustee Council support has enabled a further five years (2017-2021) of large-scale plankton data to be collected using a Continuous Plankton Recorder towed behind a commercial container ship on its route from Washington State into Cook Inlet. Sampling occurred monthly, six times between spring and autumn each year. Methodology was unchanged from previous projects. Plankton were filtered onto a slowly moving band of 270 µm mesh as the ship towed the instrument along the transect. The mesh was subsequently cut into discrete 18.5 km sections (containing about $3m^3$ of filtered seawater) and the plankton retained in each sample analyzed using a microscope to give taxonomically resolved abundances. Ship's log information was used to allocate each sample mid-point a time, date, and geographic location. All shelf samples were analyzed, and then archived. A temperature logger was also attached to the Continuous Plankton Recorder to record in situ temperature along the transect.

The last two years of the five-year project summarized here suggests that the plankton within the Alaskan shelf may be returning to more typical sub-arctic communities following the marine heatwaves of 2016 and 2019. A prolonged warm period began with anomalous warm water offshore in summer 2013 (also known colloquially as "the Blob"), which was visible in temperature data collected on the shelf in autumn 2013 and was succeeded by a strong El Niño, leading to a period of roughly seven years of unusually warm conditions (Suryan et al. 2021). Data shown in this report reveal that the plankton communities on the shelf were affected by this anomaly. Zooplankton were quite abundant, higher than average in the summer, but were biased towards smaller taxa. Warm water copepods were more numerous than average. The plankton communities were thus different (and for an extended period of time) from those sampled in other years. Large diatoms were low during this warm period, either through increased grazing by the higher numbers of zooplankton or unfavorable nutrient availability caused by the oceanographic conditions, including increased water column stability. Data from 2020 and 2021 show that large round diatom numbers were rebounding and the numbers of large copepods and euphausiids have increased. We also found that the relationship between low diatom abundance and low first year growth in juvenile herring has continued throughout the last five years of sampling.

INTRODUCTION

The *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) support has contributed to a larger effort to use Continuous Plankton Recorders (CPRs) to collect lower trophic level samples from the North Pacific and describe changes occurring in the plankton in the North Pacific. The Pacific CPR program was initiated following a recommendation from the North Pacific Marine Science Organization (PICES 1998) that the CPR be used to address the lack of consistent, seasonal, large-scale plankton data. CPRs have been deployed for over 90 years in the North Atlantic from

Ships-of-Opportunity, providing a wealth of time series data (Reid et al. 2003). Prior to the start of the Pacific CPR program, the North Pacific had only a few regional zooplankton time series, and the CPR offered the most cost-effective way to sample larger areas on a seasonal basis.

A CPR survey has been in place in the region since 2000 using commercial ships to tow CPRs on two regular routes in the North Pacific. EVOSTC final reports for projects 02624-BAA, 030624, 040624, 070624, 12100624 and 16120114 give details of previous findings based on EVOSTC support. This report updates the survey results but has been more integrative during the last ten years through the inception of the EVOSTC Long-term Research and Monitoring Programs in 2012.

The spill-affected area is an oceanographically complex subarctic shelf ecosystem and the valuable marine resources that are found here (e.g., herring, salmon, marine birds, and mammals) experience naturally induced variability on several scales, as well as being impacted by catastrophic events such as the oil spill. Natural, rather than human-related, processes known to influence this region are many; on seasonal and interannual time scales the strength of the Alaskan shelf and Alaskan Coastal currents are mediated by freshwater run-off and winds (Royer 1979, Stabeno et al. 2004, Weingartner et al. 2005), persistent coastal downwelling in contrast to most eastern Pacific boundary regions, and eddy-mediated cross-shelf transport of organisms and nutrients (Okkonen et al. 2003, Ladd et al. 2005). More quasi-decadal time scale influences are the change in sign of the Pacific Decadal Oscillation (PDO, Mantua et al. 1997). Historically, the PDO has been a useful indicator of weather patterns that persist for a decade or more but has more recently been switching state approximately every five years. Positive (negative) PDO values are associated with warmer (cooler) than normal conditions in the Northeast Pacific. A second, medium time-scale influence is the North Pacific Gyre Oscillation (NPGO), a climate pattern that emerges as the second dominant mode of sea surface height variability in the Northeast Pacific Ocean (Di Lorenzo et al. 2008). When the NPGO index is positive the westerly winds over the eastern North Pacific are often stronger than normal, influencing the circulation processes. Moderate to strong El Niño and La Niña events are also felt on the Alaskan shelf (Weingartner et al. 2002). Regime shifts, which may be triggered by the climate processes described above, have periodically occurred with lower frequency, such as the 1976 shift, which changed Alaskan fisheries from shrimp to fish dominated (Francis and Hare 1994). More recently, anomalous warming across a wide expanse of the Northeast Pacific occurred late in 2013 and persisted through 2014 (Bond et al. 2015). Nicknamed "the Blob" and succeeded by a strong El Niño in 2015, the Alaskan shelf has been influenced by these strong marine heatwaves for much of six consecutive years (Di Lorenzo and Mantua 2016, Amaya et al. 2020).

Plankton have short life cycles and limited mobility, so they often respond rapidly to changes in their environmental conditions. They also support many of the marine food webs that result in valuable marine resources, and this provides the rationale behind the CPR program. Results presented here integrate the plankton observations with physical forcing data collected during the FY17-21 Gulf Watch Alaska program to try to understand temporal variability in the plankton, particularly during the recent unusually warm conditions. We have recently shown that during the marine heatwave an absence of forage fish (Arimitsu et al. 2021) led to a top-down effect on the plankton, such that zooplankton were not grazed as greatly and so were more abundant (Batten et al. 2022). In turn, zooplankton exerted a heavy grazing pressure on the diatoms which were consequently low in abundance (Batten et al. 2022). This is another example of how oceanographic variability propagates through the food web from plankton to fish.

OBJECTIVES

The objective of the CPR project is to provide consistent large spatial scale data on plankton populations of the Alaskan Shelf to extend the existing time series and integrate the data with other regional sampling. More specifically, we have provided monthly (spring to fall – typically April to September) sampling of zooplankton and large phytoplankton along the transect from the oceanic Gulf of Alaska to Cook Inlet, analyzing every 4th oceanic and every shelf sample to provide taxonomically resolved abundances.

METHODS

CPR surveys are conducted in oceans throughout the globe and follow consistent and comparable methods. A full description of the CPR instrument and sampling is given in Batten et al. (2003), and Richardson et al. (2006) describe data analysis methods.

Plankton sample collection

The CPR is supplied to the ship (cargo vessel Matson Kodiak) with sufficient internal cassettes preloaded with filtering mesh and formaldehyde preservative to cover the sampling transect. Each cassette is deployed for a maximum of ~800 km (450 nautical miles), after which the crew recovers the CPR, changes the cassette, and redeploys it (normally within 30 minutes of recovery, unless activities of the ship prevented this). The ship's officers keep a log of deployment and recovery positions and any course changes.

Water and plankton enter the front of the CPR through a small square aperture (1.27 cm), pass along a tunnel, and then through the silk filtering mesh (with a mesh size of 270 µm), which retains the plankton and allows the water to exit at the back of the machine. The movement of the CPR through the water turns an external propeller which, via a drive shaft and gearbox, moves the filtering mesh across the tunnel at a rate of approximately 10 cm per 18.5 km of tow. As the filtering mesh leaves the tunnel it is covered by a second band of mesh so that the plankton are sandwiched between these two layers. This mesh and plankton sandwich is then wound into a storage chamber containing buffered 40% formaldehyde preservative (which dilutes in the seawater to a concentration of about 4%, sufficient to fix and preserve the plankton). As the ship approaches port in Anchorage the CPR is recovered for the final time and stored onboard until the ship docks. At this time the mechanisms are offloaded and collected by technicians from Kinnetic Laboratories in Anchorage, who have been previously trained in CPR servicing. The samples are unloaded and sent to the laboratory in British Columbia for processing while the gear is serviced, reloaded with filtering mesh, and returned to the ship for the next transect. The towed mesh is processed according to standard CPR protocols; first cut into separate samples (each representing 18.5 km of tow and about 3 m^3 of seawater), which are randomly apportioned amongst the analysts for plankton analysis. Every fourth sample in the open ocean is analyzed with the remainder being archived, but over the Alaskan shelf consecutive samples are processed. The ship's log is used to determine the mid-point latitude and longitude of each sample (shown in Fig. 1), along with the date and time.

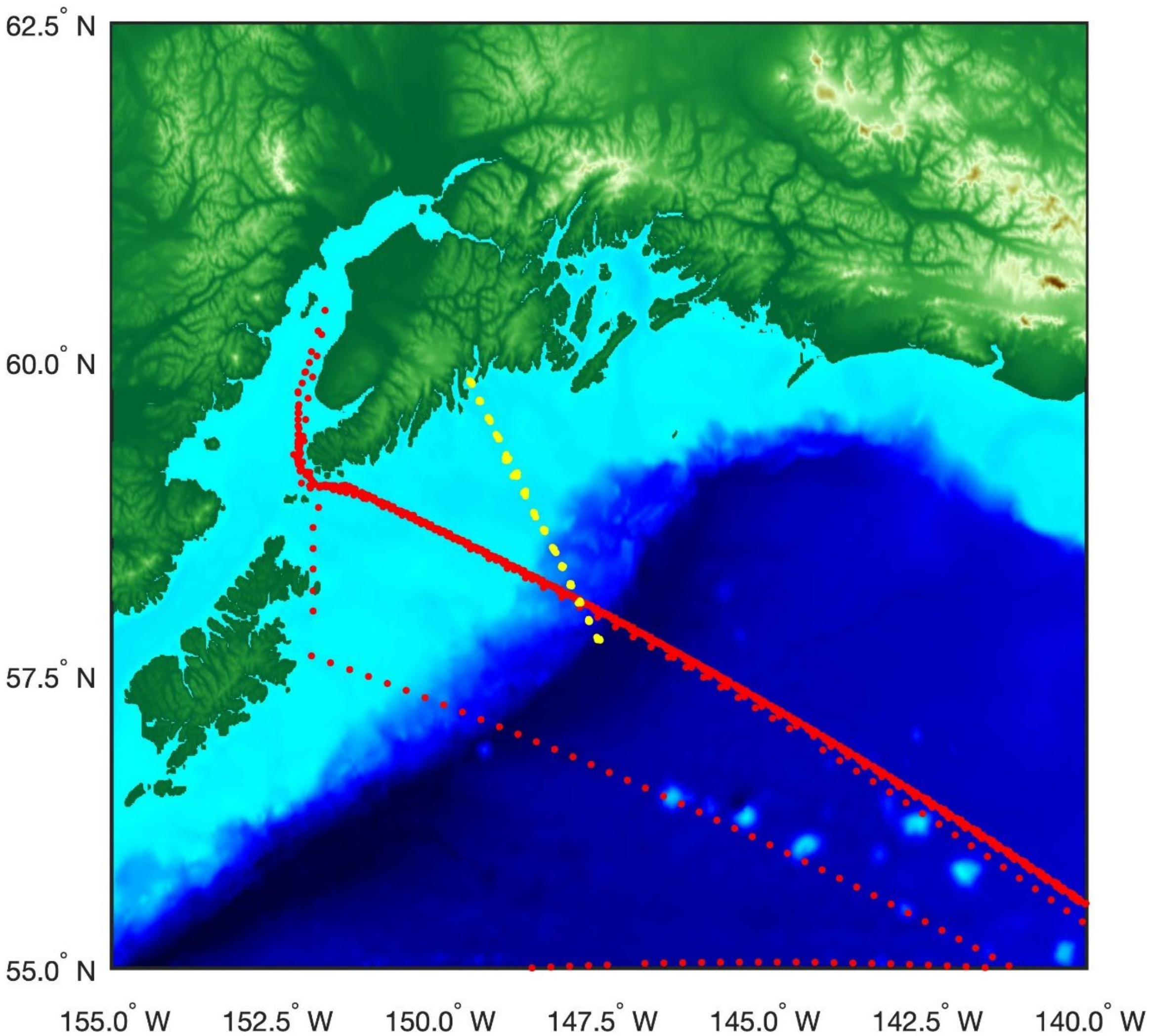

Figure 1. Location of all Continuous Plankton Recorder samples collected in the northern Gulf of Alaska during this project's duration (2017-2021, red circles). Note the consistency of the north-bound transect; there are 30 separate monthly transects but they overlap almost entirely. One of the transects had to be towed south bound. Seward Line stations are shown as yellow circles.

Taxonomic analysis
The first step in taxonomic analysis is the assessment of phytoplankton color (the greenness of the sample, or Phytoplankton Color Index), which was determined by comparison with standard color charts. This is a semi-quantitative representation of the total phytoplankton biomass and includes the organisms that are too fragile to survive the sampling process intact, but which leave a stain on the mesh. Hard-shelled phytoplankton are then semi-quantitatively counted under a purpose-built microscope by viewing 20 fields of view (diameter 295 µm) evenly spaced across each sample under high magnification (x 450) and recording the presence of all the taxa in each field. Abundance is then gauged as presence in the number of fields, e.g., presence in 20 fields is assumed to reflect a more abundant organism than presence in 2 fields. Small zooplankton are then identified and counted from a sub-sample by tracking across the filtering mesh with the microscope objective (a 2 mm diameter field of view = 2% of the sample width) whilst all zooplankton larger than about 2 mm are removed from the mesh and counted without sub-sampling. Identification in all cases is carried out to the most detailed practicable taxonomic level and is a compromise between speed of analysis and scientific interest. For example, since copepods make up the majority of the zooplankton most copepods are identified to species level whilst rarer groups, or those not preserved well by the sampling mechanism (such as chaetognaths), are identified to a lower level. A list of taxa and their abundance category on each sample is thus generated, and from this summary indices (such as zooplankton biomass, diatom abundance) can also be calculated.

Full, quality-controlled data are normally available 9-12 months after collection. To get a more rapid 'first look' at each transect a portion of the samples were processed within 2 months of the ship's return. Every 16th off-shelf sample and every 4th shelf sample is processed rapidly. This represents 25% of the total samples that are eventually processed. Quality control is carried out following a routine procedure developed for the Atlantic CPR survey: After all samples on a transect have been processed, adjacent samples are compared and counts that differ significantly from both adjacent samples are sent back for re-counting of the taxa concerned. Once the count has been checked and required corrections are made, the final data are entered into the database.

Collection of temperature data
A small self-powered, self-logging temperature recorder (Vemco Minilogger^{TM}) is attached to the tail section of the CPR. This unit records temperature at the depth of the CPR every 10 minutes and the ship's log is then used to estimate a position for each temperature record.

RESULTS

Sampling
The objectives described above were met fully, with 6 transects being sampled each year (Table 1). Spacing between sampling was typically monthly as planned. Sometimes six weeks

occurred between samplings to accommodate the technicians' schedule or to lengthen the field season (for example, July to September 2018).

Table 1. Dates for each Continuous Plankton Recorder transect sampled during this project.

Year	Transect number	Dates	Year	Transect number	Dates
2017	1	27-30th April	**2018**	1	14-17 April
	2	27-30 May		2	17-20 May
	3	30 June -2 July		3	16-19 June
	4	29 July -1 Aug		4	19-22July
	5	31 Aug -3 Sept		5	24-27 Sept
	6	30 Sept -3 Oct		6	20-23 Oct
2019	1	11-14 April	**2020**	1	2-5 May
	2	11-14 May		2	4-6 June
	3	13-15 June		3	4-6 July
	4	13-15 July		4	7-9 Aug
	5	15-18 August		5	6-8 Sept
	6	15-17 Sep		6	8-11 Oct
2021	1	15-17 April			
	2	15-18 May			
	3	17-20 June			
	4	17-20 July			
	5	19-22 Aug			
	6	19-21 Sept			

Time series results

Although data prior to 2017 were collected under previous contracts, for consistency with other Gulf Watch Alaska reports we are including pre-2017 data here, too. The data from 2020 have been finalized. Data from 2021 are included in the following figures; however, it is important to note that not all of the samples have been analyzed yet and data are currently being finalized in the laboratory. Sea Surface Temperature (SST) data from 2004 to 2021 were obtained from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS, 1° enhanced data, www.esrl.noaa.gov/psd/data/gridded/data.coads.1deg.html) for the Alaskan shelf region to characterize the physical environment. Results show that interannual variability in plankton dynamics is high and the plankton responded clearly and rapidly to the warm conditions of 2014-2016 and 2019 (Figs. 2 and 3), with changes evident in abundance, composition, and timing.

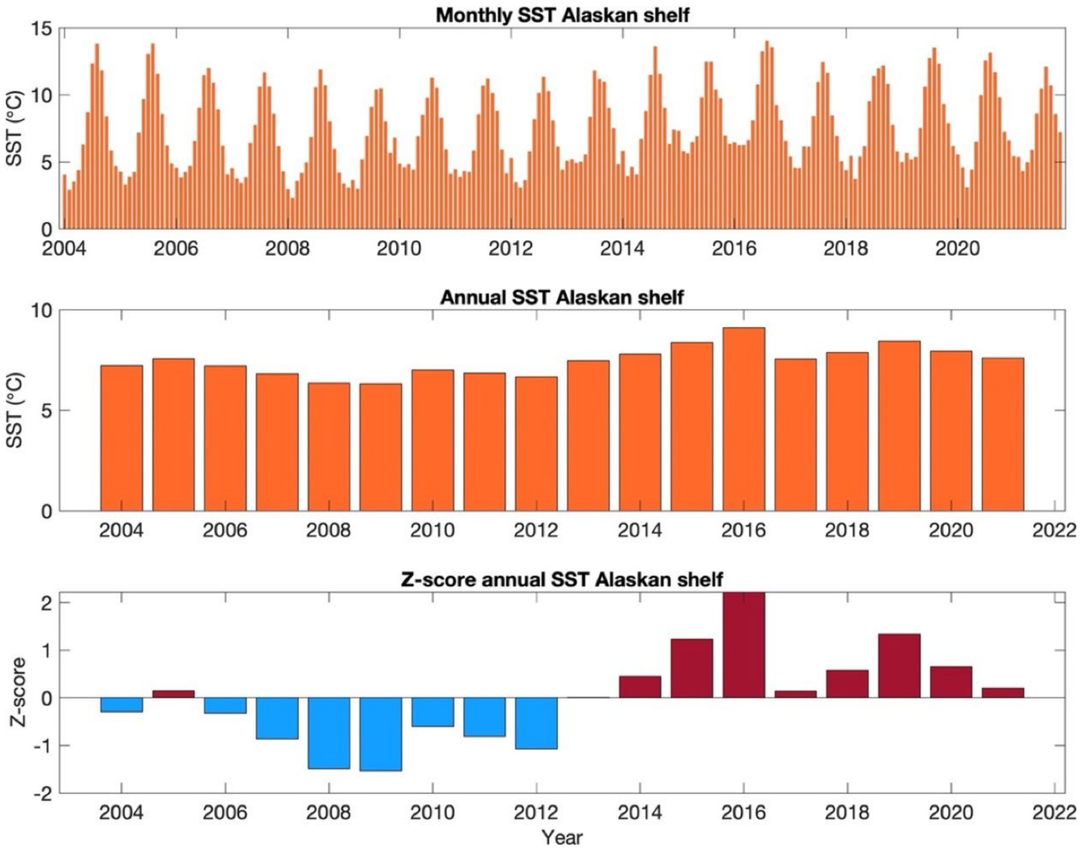

Figure 2. Monthly mean, annual mean, and annual standardized z-score Sea Surface Temperature (SST) within the Alaskan shelf region from 2004 to 2021. Where positive z-score values signify values above the mean (red) and negative values are below the mean (blue).

Fig. 3 shows the annual abundance of diatoms and small copepods. The results for 2019 suggest a similar situation to that of 2014-2016, where warm temperatures correspond to high numbers of small copepods and low numbers of diatoms, although it is short lived. Fig. 4 demonstrates this trend towards high numbers of small copepods and low numbers of diatoms during the warmest years, 2016 and 2019.

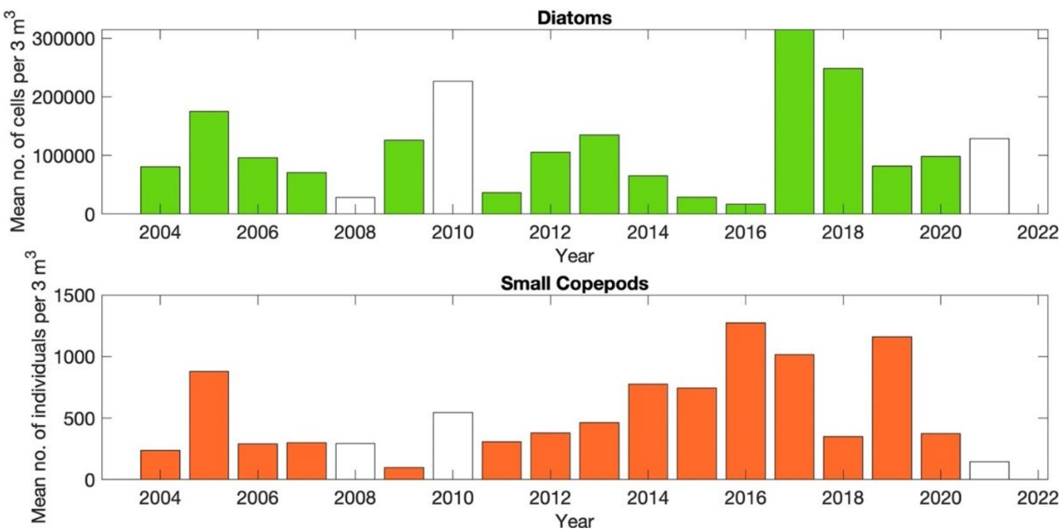

Figure 3. Mean annual abundance of diatoms (green bars) and small copepods (<2mm total length, orange bars) from shelf samples near Cook Inlet. Unfilled bars are years when sampled months <4 and so data are not as robust. Note: 2021 data are provisional.

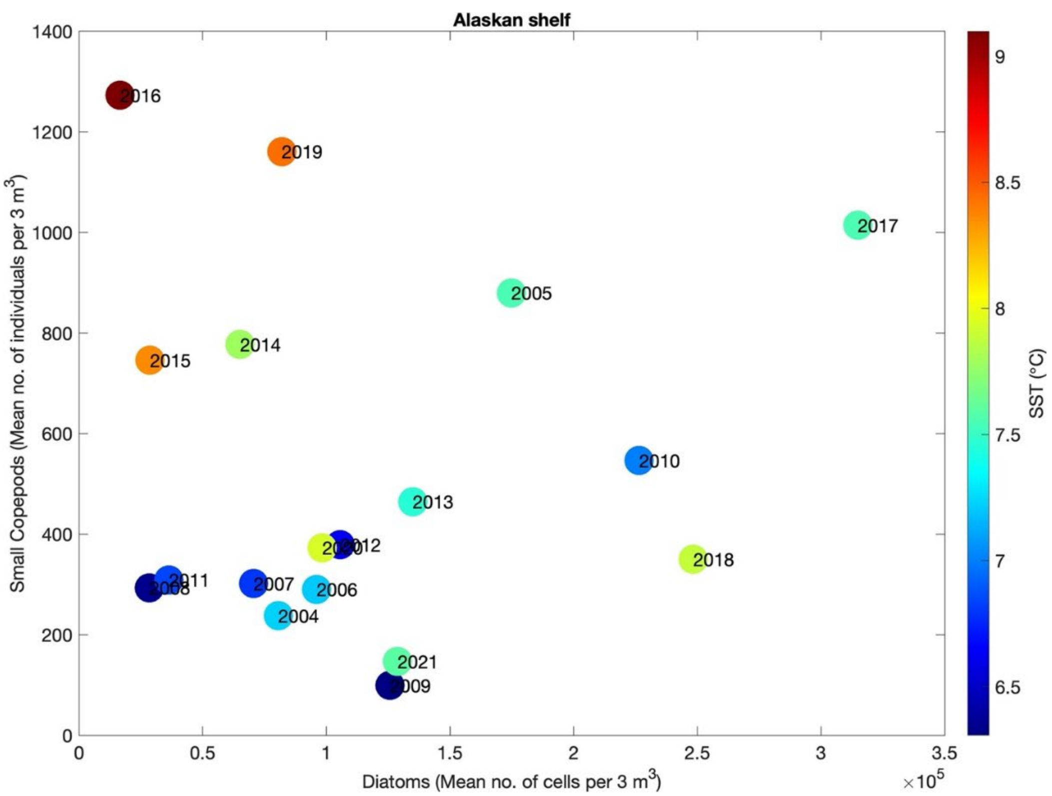

Figure 4. Mean annual abundance of diatoms versus small copepods (<2mm total length, orange bars) from shelf samples near Cook Inlet, labelled by year and colored by annual Sea Surface Temperature (SST). Note: 2021 data are provisional.

During years with cooler sea surface temperatures the proportion of round diatoms was greater than other groups of phytoplankton (Fig. 5). The phytoplankton community temperature index (CTI) also reflects this as those phytoplankton species that are associated with warmer waters strongly correlate with increased sea surface temperature (Fig. 6).

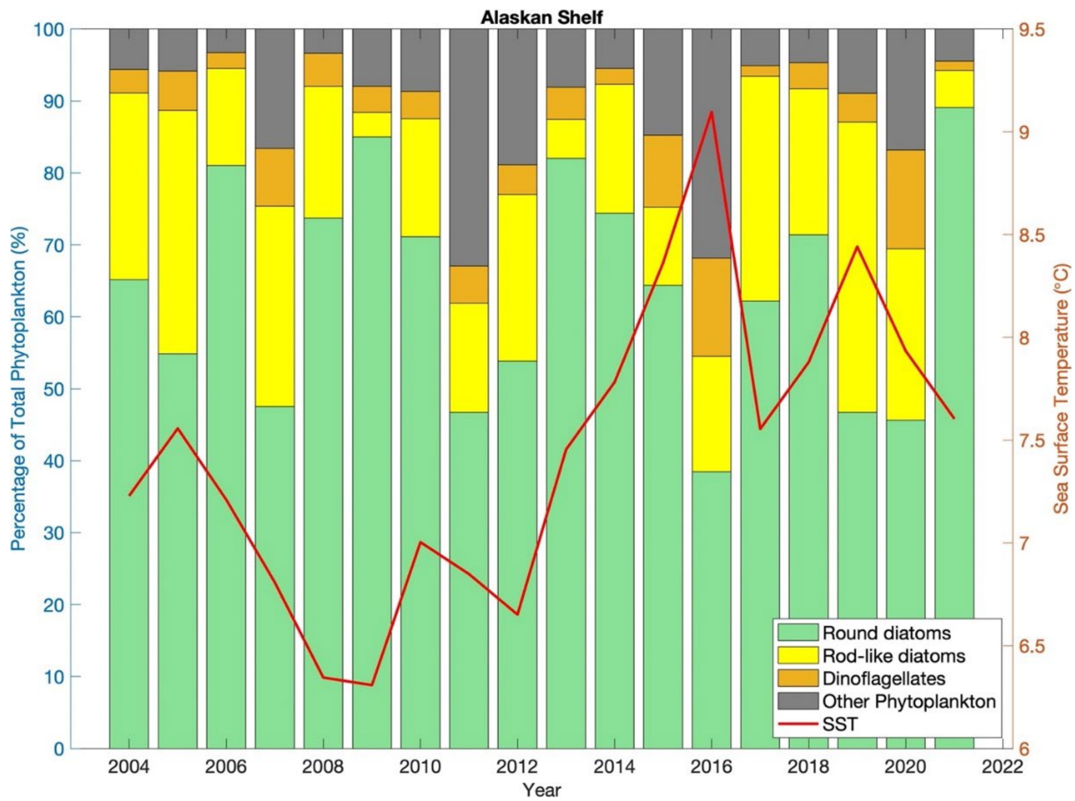

Figure 5. Contribution of phytoplankton groups to the mean annual phytoplankton community in the Alaskan shelf region. Annual Sea Surface Temperature is shown in red (right-hand axis, °C). Note: 2021 data are provisional.

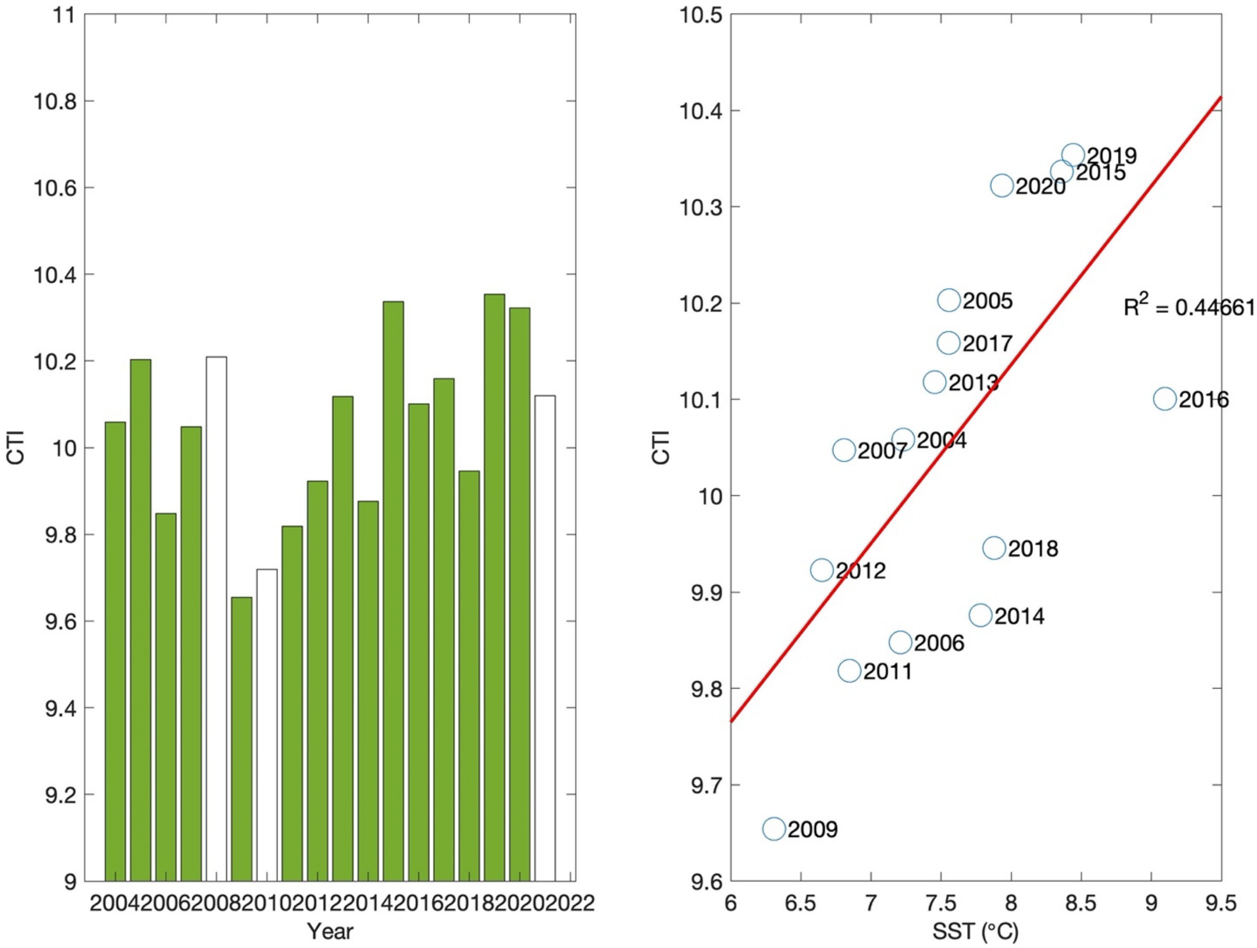

Figure 6. The mean annual phytoplankton Community Temperature Index (CTI) for the Alaskan shelf region (left) and the relationship between Sea Surface Temperature (SST) and CTI (right). Unfilled bars are years when sampled months <4 and so data are not as robust. Note: 2021 data are provisional.

Fig. 7 presents some of the common groups of zooplankton as an annual percentage from 2004 to 2021. A general pattern seems to be that during warmer years there were more counts of pteropods and lower numbers of euphausiids.

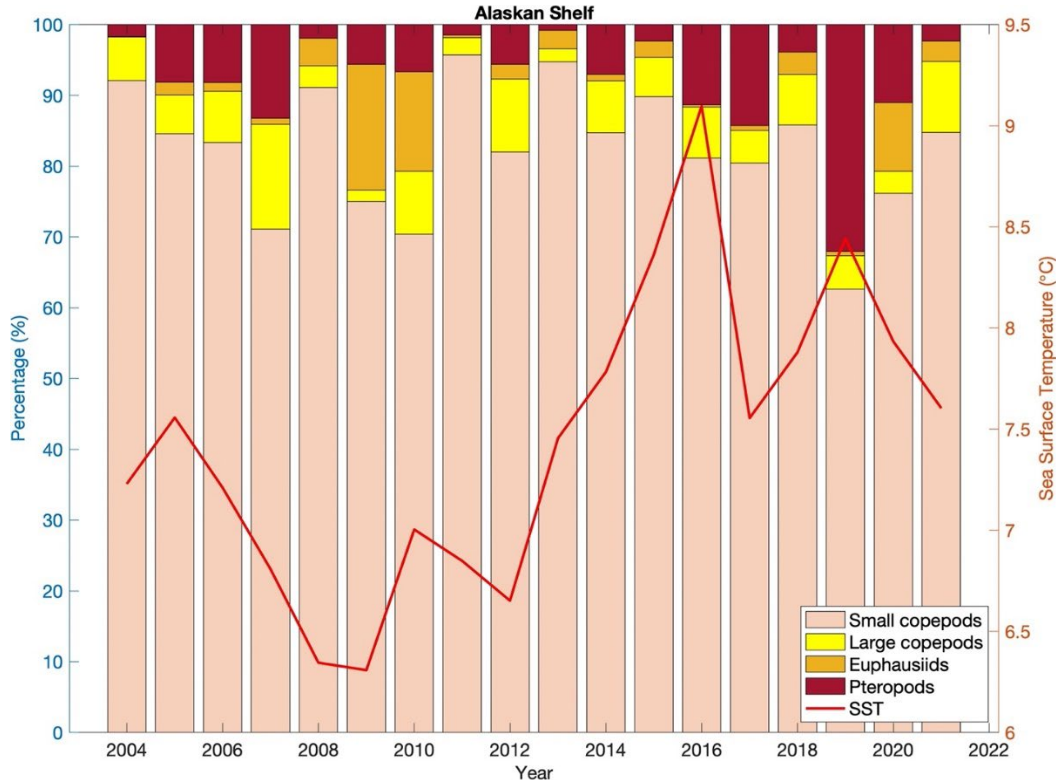

Figure 7. Contribution of zooplankton groups to the mean annual zooplankton community in the Alaskan shelf region. Annual Sea Surface Temperature is shown in red (right-hand axis, °C). Note: 2021 data are provisional.

Most copepods in CPR samples are identified to species, certainly to genus, and so changes in the abundance of specific taxa can be indicative of changing oceanographic conditions. Given that anomalous warmth was a strong feature of the last part of the sampling period, we have further examined copepod taxa that tend to have a more southerly distribution, i.e., occur in warmer water. Mean annual abundances are shown in Fig. 8 for the large copepod *Calanus pacificus* (copepodites cv-cvi), which, while ubiquitous in the north pacific, is associated with warm water. This pattern of high numbers of *Calanus pacificus* during warmer years is observed in the Alaskan shelf region, with lower numbers being recorded between 2006 and 2013 and more recently in 2020-2021.

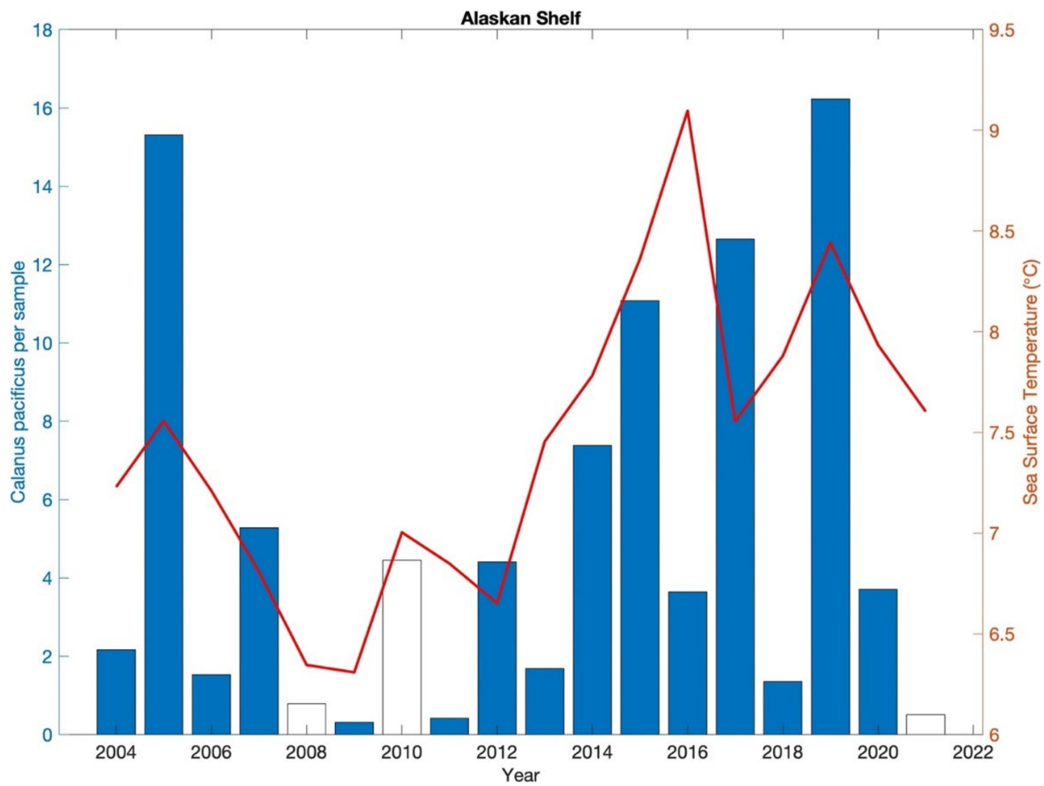

Figure 8. Mean annual abundance of the warm-water indicator zooplankton species, Calanus pacificus (blue bars), annual Sea Surface Temperature is shown in red (right-hand axis, °C). Unfilled bars are years when sampled months <4 and so data are not as robust. Note: 2021 data are provisional.

DISCUSSION

During the first five years of this project (2012-2016) the warm conditions observed in the Gulf of Alaska (2014-2016) and consistent plankton monitoring provided insights into the contrasting annual anomalies between small copepods and large diatoms, and the ecological dynamics that dictates this pattern (Batten et al. 2018). These warm conditions continued into the next period of the project (2017-2021) and led to the understanding that while small copepods were high in abundance and large diatoms were low during anomalously warm years, this was due to increased grazing by the higher numbers of zooplankton and unfavorable nutrient availability caused by the oceanographic conditions, including increased water column stability (Batten et al. 2022).

The five years of sampling described within this report (2017-2021) include large variations in SSTs, particularly the 2019 heatwave (Amaya et al. 2020, Suryan et al. 2021). The 2020 and 2021 Alaskan shelf data suggest that the plankton communities in this region may be returning to pre-heatwave (2016 and 2019) values. Batten et al. (2022) suggests that during the marine heatwave an absence of forage fish (Arimitsu et al. 2021) led to a top-down effect on the plankton, such that zooplankton were not grazed as greatly and so were more abundant. In turn they exerted a heavy grazing pressure on the diatoms which were consequently low in abundance. Another limiting factor is the concentration of nutrients; anomalously warm surface waters can increase stratification thereby reducing nutrient availability. Lower nutrients can affect the phytoplankton composition by promoting growth of smaller and narrower cells because of a relatively larger surface area over which to absorb nutrients. In turn, the size and composition of the phytoplankton will impact the zooplankton that are able to feed on them, and so the effects pass up the food chain. There have also been links made previously in Batten et al. (2016) to the first year growth of Prince William Sound herring and CPR data collected in the Gulf of Alaska. Batten et al. (2016) showed that the first-year growth of Prince William Sound herring was greater in years with higher abundances of smaller sized plankton, particularly the large diatoms (r^2=0.76, p=0.0005). This pattern appears to be continued in the last five years of sampling, as the abundance of diatoms (Fig. 3), specifically large round diatoms (Fig. 5), follows the general pattern of annual number of age-1 herring schools.

Warmer water favors certain (often smaller) taxa over others, as seen by the fact that warmer water taxa (Fig. 8) are more prevalent and there are higher CTI values during warm years (Fig. 6). Such communities may apparently persist for several years after a heatwave event, especially if waters remain warm, however it appears that after seven years of warmer than average conditions, the plankton recorded in 2020-2021 are returning to more typical sub-arctic communities. A return of average values of large copepods and euphausiids in the Gulf of Alaska could influence the food web functioning, since these taxa store more lipids to overwinter. Higher concentrations of lipids may occur when temperatures are decreased and their prey are more abundant (Hellessey et al. 2020). Interestingly, the data presented in Fig. 7 suggests that during warmer years there are more pteropods in the Alaskan shelf region. It has been suggested that this may be because pteropods use the shelf to shelter from the warmer temperatures, as it is cooler on the Alaskan shelf than in the offshore waters. This analysis is currently being investigated, and comparisons with pteropod data from the Kodiak and Seward lines may be able to shed light on this phenomenon.

CONCLUSIONS

The last five years of this project has sampled plankton during unusual, and persistent, warm conditions resulting in plankton communities on the shelf that were biased towards smaller zooplankton. Large diatoms were also low during this warm period, likely due to increased grazing and/or reduced nutrient conditions. Warm water copepods were more numerous than average. However, it appears that in the last two years of sampling (2020-2021) the plankton in the Alaskan shelf region may be returning to more typical sub-arctic communities. While we cannot be certain how changing taxonomic composition of the prey affects predators via nutritional contributions to their diet, there could be some benefits of plankton communities returning to average. The recent two years of data suggest that the region has not entered a new plankton regime that is persisting independent of local conditions, despite multiple successive warm years, and that the plankton communities are able to shift back to previous states.

ACKNOWLEDGEMENTS

We are grateful to the officers and crew of the Matson (formerly Horizon) *Kodiak*, which has sampled this transect for over 17 years and to Matson and Horizon Shipping for their voluntary involvement with the project. Funding for this study was provided by the North Pacific CPR Consortium, which comprises the *Exxon Valdez* Oil Spill Trustee Council, the North Pacific Research Board, the Canadian Department of Fisheries and Oceans, the Continuous Plankton Recorder Survey, The Marine Biological Association, and the North Pacific Marine Science Organization. Thanks also to Kinnetic Laboratories and Doug Moore and Melissa Hennekes for preparing the equipment and samples. This project is part of the Gulf Watch Alaska long-term monitoring program. These findings and conclusions presented by the author(s) are their own and do not necessarily reflect the views or position of the *Exxon Valdez* Oil Spill Trustee Council.

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