

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

Monitoring the Oceanographic Conditions of Prince William Sound

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

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July 2023

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Study History: This project materially began as project 10100132 of the Prince William Sound Herring Survey program (2009-2012), which included vessel surveys to the same stations occupied as part of this project and continued as project 12120114-E as part of the FY2012-2017 Gulf Watch Alaska program. This project was approved by the Trustee Council in 2017, and funding began in February 2018. Fieldwork for this project began in 2017 and continued until December 2021. Annual reports were submitted in 2018 through 2021. The following publications have preceded this report and are included as appendices:

Campbell, R. W., P. L. Roberts, and J. Jaffe. 2020. The Prince William Sound Plankton Camera: a profiling in situ observatory of plankton and particulates. ICES Journal of Marine Science doi:10.1093/icesjms/fsaa029.

Campbell, R.W. 2018. Hydrographic trends in Prince William Sound, Alaska, 1960–2016. Deep Sea Research. doi: 10.1016/j.dsr2.2017.08.014

Abstract: In order to track the bottom-up factors (environmental, biogeochemical and lower trophic level) that may be important for ecosystem function, systematic surveys of the Prince William Sound region were conducted between 2018 and 2021 and consisted of basic oceanographic and biological measurements (temperature and salinity; chlorophyll-a, nitrate, and zooplankton concentrations). Additionally, an autonomous profiling mooring was deployed in central Prince William Sound to capture high frequency variability of those metrics in the surface layer. Analysis of a now 47-year long time series of temperature and salinity suggests that the region is experiencing a broad warming trend. Two marine heatwaves have occurred in recent years, which altered the plankton community of Prince William Sound. Long term reductions in marine productivity seem tied to that warming trend, likely due to thinning of the seasonal mixed layer and concomitant reduction in nitrate availability. The deployment of an *in situ* camera aboard the profiling mooring provided an unprecedented glimpse into the annual patterns of numerous zooplankton taxa.

Key words: Climate, oceanography, phytoplankton, Prince William Sound, salinity, temperature, zooplankton

Project Data: Data collected during this project includes conductivity and temperature at depth (CTD) casts, depth-specific chlorophyll concentrations, and zooplankton species composition and abundance. CTD data are in text files in the format produced by the software provided by the CTD manufacturer; all data processing steps are documented in metadata headers within each file, as well as station metadata (station name, event number, longitude, latitude, date and time).

Chlorophyll and zooplankton data are in flat text files. All the data are stored electronically on the Gulf Watch Alaska Research Workspace (https://gulf-of-alaska.portal.aaos.org/#metadata/fc5b0956-ef7c-49df-b261-c8e2713887fc/project/folder_metadata/2638352).

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@aaos.org.

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

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Monitoring the Oceanographic Conditions of Prince William Sound

EXECUTIVE SUMMARY

The goal of this project was to develop a monitoring program that would return useful information on temporal and spatial changes in the physical and biological oceanography of Prince William Sound region, at a reasonable cost, and with a reasonable amount of effort. The data acquired were depth-specific (because water column stability is important to ecosystem productivity) and of high enough frequency to capture temporal changes (changes that occur on the order of weeks) and resolve spatial variability in the region. Specific objectives included:

1. Conduct systematic vessel-based surveys in Prince William Sound and at its entrances to continue the ongoing time series of physical, biogeochemical, and biological parameters while also supporting continued herring research by maintaining the existing time series (hydrography, plankton and nutrients) at the four Sound Ecosystem Assessment study bays.
2. Install and maintain an autonomous profiling mooring in Prince William Sound that will acquire frequent (at least daily) water-column profiles of the same physical, biogeochemical and biological parameters as the vessel-based surveys, plus *in situ* observations of zooplankton, large phytoplankton and other particles.

The oceanographic observations from the vessel-based surveys were combined with a now nearly five-decade long time series of temperature and salinity profiles within Prince William Sound and with profiles from the immediately adjacent shelf compiled from numerous archives. Observations matched with recent cool (2007-2013) and warm (2013-onward) periods observed in the region, and also showed an overall regional warming (0.1 to 0.2 °C per decade) trend that matches long term increases in heat transport to the surface ocean. Embedded within the generally warm conditions observed since 2013 were two marine heatwaves, in 2013-2015 and again in 2019. Those events drastically impacted the entire marine ecosystem of the region and altered the species composition of the plankton in PWS.

The autonomous oceanographic profiler was deployed seasonally at a site in central PWS from 2017 through 2021. The goal of the project was to deploy the profiler from spring through autumn to capture the evolution of the surface oceanography, plankton dynamics, and nutrient biogeochemistry over the growing season. The profiler conducted twice daily profiles from 60 m depth to the surface, from approximately March to November each year (with some delays and occasional breakdowns) and provided a high-resolution record of the evolution of the local surface oceanography of PWS each year, as well as the productivity by primary producers. An *in situ* camera system developed for the profiler provided observations of several million individual plankters, which were identified to the finest taxonomic level possible with a neural network based machine vision classifier. The resulting observations produced unprecedented records of

interannual and high frequency intra-annual depth distributions of numerous common plankton groups. *In situ* imagery with automated classification holds promise for the rapid assessment of plankton populations.

INTRODUCTION

Marine ecosystems are not static over time, they may change gradually from year to year or shift abruptly; those changes are in part driven by bottom-up factors, such as environmental changes (e.g., temperature, salinity, turbidity) and biogeochemical interactions (the availability and recycling of nutrients). Long term monitoring of the spill-affected area is important, both to assess the recovery of resources, and to understand how the ecosystem is changing over time.

The ecosystems of the Prince William Sound (PWS) region are influenced by physical environmental factors: metabolic and other vital rates for lower trophic species are generally temperature controlled, and water column production is ultimately limited by the amount of nitrogen made available to primary producers each year. Nitrogen availability is influenced by stratification (i.e., the onset of a seasonal thermocline or halocline) and mixing processes. These physical factors vary in space and in time, with different locations having different drivers (e.g., tidewater glaciers vs riverine estuaries, watersheds of varying size), and those parameters also change both inter- and intra-annually. Superimposed over all those changes in the physical environment are myriad changes in the marine ecosystem, both in terms of the constituents (who is there) and abundance (how many there are, or their biomass). The phenology of ecosystem components (the timing of who appears) is also important, particularly with regards to matches and mismatches between predators and prey.

The deep waters of the North Pacific are the terminus of the Great Ocean Conveyor (Broecker 1991), which accumulates remineralized nutrients from several centuries of detritus flux to depth. Those nutrient-rich deep waters are mixed onto the continental shelf, where they fuel very high primary productivity (Behrenfeld and Falkowski 1997), that is transferred up the food web to higher trophic levels (Ware and Thompson 2005).

Primary productivity in the Gulf of Alaska (GOA) is highly seasonal and thought to be mediated by the availability of light and water column stability (Henson 2007). There is usually a large bloom each spring that depletes surface nutrients (primarily nitrate: Childers et al. 2005), a period of relatively low productivity through the summer months, and potentially a smaller autumn bloom as stability breaks down. The canonical hypothetical mechanism for spring bloom formation is the Critical Depth Hypothesis (Sverdrup 1953) whereby bloom initiation occurs after stability reaches a critical depth whereby growth exceeds losses. Recent work elsewhere has suggested that the Critical Depth Hypothesis does not necessarily hold, and that bloom formation may occur in winter, leading to the Dilution-Recoupling Hypothesis of Behrenfeld (2010), which explicitly includes zooplankton grazing.

PWS is a large and complicated estuarine-fjord system with numerous sub-basins around its margins. It is separated from the GOA by several large islands and surrounded on its three landward sides by the Chugach Mountains. The surface waters of PWS receive considerable freshwater inputs, from streams, rivers, and icefields, as well as considerable sediment loading. PWS is immediately downstream of the Copper River delta, the largest point source of fresh water to the GOA, which produces a turbid plume that travels westward along the coast into PWS through Hinchinbrook Entrance. PWS is also connected to shelf waters via the Alaska Coastal Current (ACC; Royer 1981), which may flow in through Hinchinbrook Entrance as well. Circulation in central PWS is usually cyclonic and driven by local winds (Vaughan et al. 2001, Okkonen and Belanger 2008), although there may be occasional reversals (Niebauer et al. 1994). The depth of the main basin is approximately 350 m (although there are some basins in the western part that are 700 m deep), while the depth of the sill at Hinchinbrook Entrance is approximately 200 m deep. Deep water renewal events occur in PWS but are not well described; renewal is likely set up during the summer and autumn by the on-shelf movement of deep water (Weingartner 2005, Halverson et al. 2013).

Within PWS, variations in annual productivity have been posited to vary based on the variations in upwelling/downwelling and the track of the ACC (the River-Lake hypothesis of Cooney et al. 2001a). Some support was found for this hypothesis for some years (1981-1991), but not in others (Eslinger et al. 2001). During winter, nutrient availability is high, as deep, nutrient-rich water is mixed to the surface. Phytoplankton production during the winter is light-limited, with a vernal bloom following the onset of stratification in the spring. Stratification is driven by the balance between the stabilizing inputs of freshwater and heat and the destabilizing influence of wind and tidal mixing. PWS is destabilized by negative heat flux and tidal mixing in the winter and stabilized by freshwater and heat inputs in the summer (Eslinger et al. 2001, Henson 2007). In general, the spring bloom starts in PWS in March to April (Weingartner 2005) and is temporally broad, occurring into June or even July (Henson 2007). PWS may also experience an autumn bloom, as stability breaks down and nutrients are moved to the surface (Eslinger et al. 2001).

The numerical and biomass dominant zooplankton in PWS is *Neocalanus* spp. (two closely related congeners, *N. plumchrus* and *N. flemingeri*), which overwinters at depths >300 m. In mid-winter (December onward), overwintering copepodids molt to adulthood and spawn at depth. Eggs and nauplii migrate to the surface, and development progresses rapidly (usually in conjunction with the spring bloom); upon reaching the penultimate copepodid stage, individuals descend to depth and enter a diapause state. Following the spring bloom, smaller bodied copepods predominate (*Pseudocalanus*, *Acartia*), and *Metridia* becomes more common in summer-autumn (Cooney et al. 2001b). Several krill species are also present but are less common and less easily sampled.

PWS is also a productive habitat for fish, including several forage fish species (Pacific herring [*Clupea pallasii*], capelin [*Mallotus villosus*], and sand lance [*Ammodytes hexapterus*]; Willette

et al. 1997), and several species important in commercial and subsistence fisheries (Pacific salmon [*Oncorhynchus* spp.], walleye pollock [*Gadus chalcogrammus*], Pacific cod [*G. macrocephalus*], and Pacific halibut [*Hippoglossus stenolepis*]). PWS is a particularly important rearing habitat for juvenile pink salmon (*O. gorbuscha*) and herring, with pink salmon feeding on zooplankton during the spring bloom, and herring primarily in late summer/autumn (Cooney et al. 2001a).

Warming trends have been observed globally for many years (Levitus et al. 2001), and those trends have also been observed in Alaska (Shulski and Wendler 2008, Campbell 2018). Much of the increased heat flux has been taken up by the ocean (Barnett et al. 2005), and warming trends have been observed in coastal Alaska at the regularly sampled Gulf of Alaska (GAK) line near Seward, Alaska (Royer and Grosch 2006, Janout et al. 2010). Since late 2013, sea surface temperature anomalies throughout the GOA have been as much as 3-4°C above average; the leading hypothesis for that particular anomaly (a marine heatwave colloquially referred to as “The Blob”) is a reduction in winter heat flux leading to residual heat being retained by the surface ocean (Bond et al. 2015). 2015-2016 was also the second strongest El Niño event on record (NOAA 2016), which generally correlates with higher-than-average surface temperatures. A second marine heatwave occurred throughout the Gulf of Alaska in the summer of 2019 (Amaya et al. 2020).

OBJECTIVES

The goal of this program was to develop a monitoring program to return useful information on temporal and spatial changes in the marine environment in PWS, at a reasonable cost. The data were to be depth-specific (because water column stability is important to ecosystem productivity), of sufficient frequency to capture temporal variability (changes that occur on order of weeks) and give an idea of spatial variability in the region. As well, given that PWS herring was a funding priority of the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) for many years, the long-term monitoring efforts were integrated with herring studies as much as possible, as well as building upon ongoing work funded by the Trustee Council. Specific objectives were:

1. Conduct regular surveys in PWS and its entrances to continue the ongoing time series of physical, biogeochemical, and biological parameters while also supporting continued herring research by maintaining the existing time series (hydrography, plankton, and nutrients) at the four Sound Ecosystem Assessment (SEA) study bays.
2. Install and maintain an autonomous profiling mooring in PWS that will conduct frequent (at least daily) profiles of the same physical, biogeochemical, and biological parameters as the surveys, while simultaneously acquiring in situ observations of zooplankton, large phytoplankton, and other particles.

METHODS

Vessel-based surveys were conducted 5-6 times per year, visiting the four SEA bays (Eaglek, Simpson, Whale, and Zaikof) that have been a focus of prior EVOSTC-funded research, as well as Hinchinbrook Entrance, Montague Strait, and central PWS (Fig. 1, red dots). Each station included a conductivity and temperature at depth (CTD) cast, water samples for nutrient and chlorophyll-a analysis, and a zooplankton tow (a 202 μm mesh, 60 cm diameter bongo net). Two stations were sampled in each of the bays, one near the head where juvenile herring are more frequently encountered, and one in more open waters at the mouth of the bay where older age classes are more common. The timing of the surveys was structured around the “productivity season” to attempt to capture the spring and autumn blooms (i.e., pre-bloom, bloom, and post-bloom).

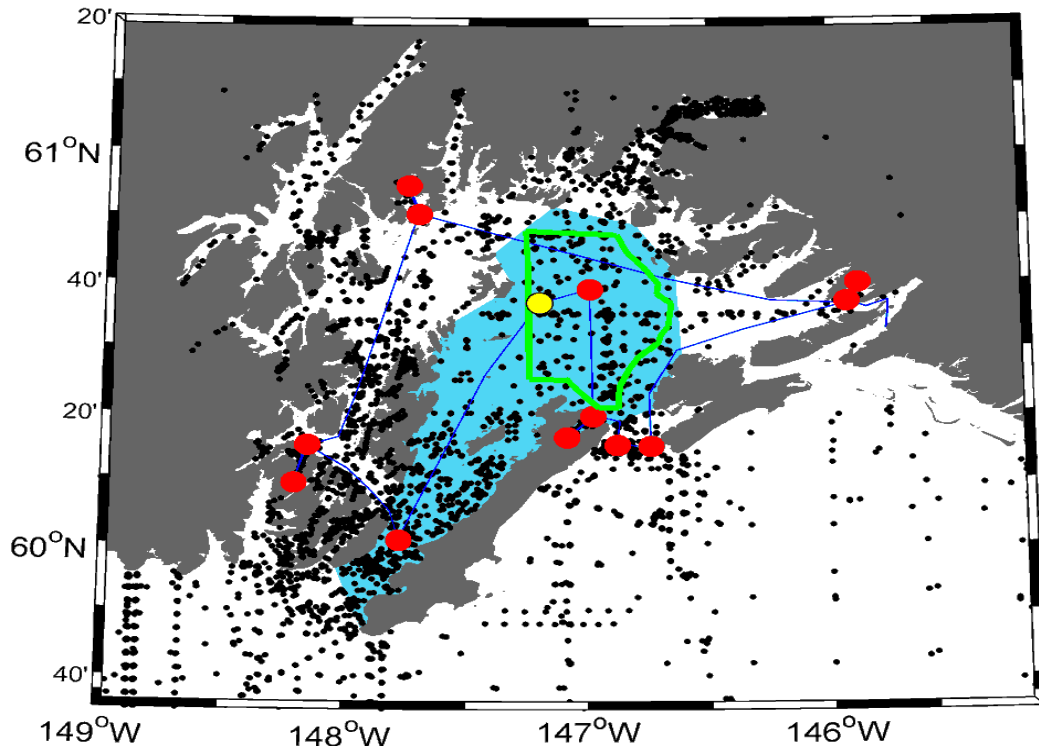


Figure 1. Prince William Sound (PWS). Black dots indicate the position of conductivity and temperature at depth (CTD) casts done 1974-2019. Red dots indicate the stations visited during vessel surveys (this study), and the blue line indicates the standard vessel track. The yellow dot indicates the position of the autonomous profiling mooring. The blue area is the “central PWS” region that was used for the determination of anomalies (see Fig. 2). The green polygon is the area within which moderate resolution imaging spectroradiometer (MODIS)/sea-viewing wide field-of-view sensor (seaWIFS) chlorophyll data were averaged.

The Seabird SBE25plus CTD used in the surveys has an initial accuracy of ± 0.001 °C and ± 0.0003 S/m for temperature and salinity; and drift between annual calibrations has been on order of 0.0002 °C/year and 0.0003 PSU/month, respectively. The Wetlabs FLNTU fluorometer/turbidometer has a resolution of 0.01 $\mu\text{g/l}$ chl-a and 0.01 NTU, and the Seabird SBE43 oxygen sensor has an accuracy of $\pm 2\%$ of saturation and a drift of $\sim 3\%$ per year. Extracted chlorophyll-a has a detection limit of 0.05 $\mu\text{g/l}$.

The patchiness of the long-term dataset in space and time (e.g., see Fig. 1) confounds standard time series analysis, and some spatial binning is required to produce time series that are dense enough to analyze. At present, spatially binned data (such as the blue area in Fig. 1) are seasonally detrended with a second order cosine function, anomalies determined from the residuals, and used to detect long term trends (Campbell 2018; Appendix A).

A time series of surface chlorophyll concentrations in central PWS was assembled from sea-viewing wide field-of-view sensor (SeaWiFS) and moderate resolution imaging spectroradiometer (MODIS) satellite chlorophyll products downloaded from the National Oceanic and Atmospheric Administration (NOAA) CoastWatch Program (data products erdSW2018chl1day and erdMH1chl1day, respectively). Daily mean and standard deviations within non-cloud-masked pixels in central PWS (inside the green polygon in Fig. 1) were calculated. The polygon was selected to avoid coastline contamination, and to avoid Copper River water, which has high turbidity which can manifest as spurious chlorophyll observations. The SeaWiFS and MODIS data were examined for an offset between the two during years when the two time series overlapped (2003-2010). SeaWiFS chlorophyll estimates tended to be slightly lower than MODIS estimates (slope = 0.88, intercept = 0.7749) and were adjusted to make the estimates comparable.

The annual cycle of the zooplankton assemblage in PWS was described by McKinstry and Campbell (2018). Following McKinstry et al. (2020), McKinstry and Campbell (2018), and Peterson et al. (2017), for this report zooplankton concentrations were converted into anomalies for subsets of species that are indicative of warmer waters (*Calanus pacificus*, *Clausocalanus*, *Corycaeus anglicus*, *Ctenocalanus vanus*, *Mesocalanus tenuicornis*, and *Paracalanus parvus*), and those that represent cooler water taxa that reflect the canonical subarctic zooplankton assemblage (*Neocalanus plumchrus*, *N. flemingeri*, *Acartia longiremis*, *Calanus marshallae*, *Oithona similis*, and *Pseudocalanus* sp.). Concentrations were $\log_{10}+1$ transformed, and monthly averages calculated; anomalies were then calculated as the difference between monthly averages and the overall mean for all observations in that given month.

The autonomous profiling mooring was deployed in central PWS near Naked Island (Fig. 1, yellow dot). The site is the same location occupied by a surface buoy deployed during the SEA project (Eslinger et al. 2001) and co-located with a sampling site sometimes occupied during University of Alaska Fairbanks Seward line cruises. The mooring is an Autonomous Moored Profiler (AMP; WetLabs, Inc.). The AMP is a self-contained positively buoyant float that is

capable of profiling from ~60 m to the surface, via an onboard winch that pays out and retrieves a thin (4 mm ultra-high molecular weight polyethylene) tether. The system is powered by an onboard 1.5 kWh battery, which allows ~60 profiles from 60 m to the surface per charge (i.e., 30 days of twice-daily profiles). The instrument payload on the AMP includes a Seabird SBE16 CTD (0.01 °C, 0.001 S/m resolution), a Wetlabs FLNTU fluorometer/turbidometer (0.01 µg/l chl-a and 0.01 nephelometric turbidity unit NTU] resolution), and an ultraviolet (UV) nitrate analyzer (a Satlantic SUNA: 2 µM resolution). The profiler underwent significant upgrades in early 2016, including new controller electronics and new communications hardware. An in situ camera system was developed in collaboration with researchers at the Scripps Institution of Oceanography, it samples ~700 ml of water at 4 Hz, with a pixel resolution of ~15 µm. A neural network-based classification system has been developed to identify the many millions of plankton images that have been collected (Campbell et al. 2020; Appendix B).

RESULTS

Hydrography

Annual cycles and long-term trends in the hydrography of PWS were described by Campbell (2018; Appendix A). Temperatures in central PWS have continued to be above average since late 2013 (Fig. 2), corresponding with the “Blob” marine heatwave observed basin wide. Contemporary data showed a weak cooling trend into early 2018 to depths >50 m, and a brief period of negative anomalies, with anomalies again trending warmer than average in late 2018 and 2019. Weakly negative anomalies were observed again in 2021, and near-surface temperature anomalies were again high in early 2022.

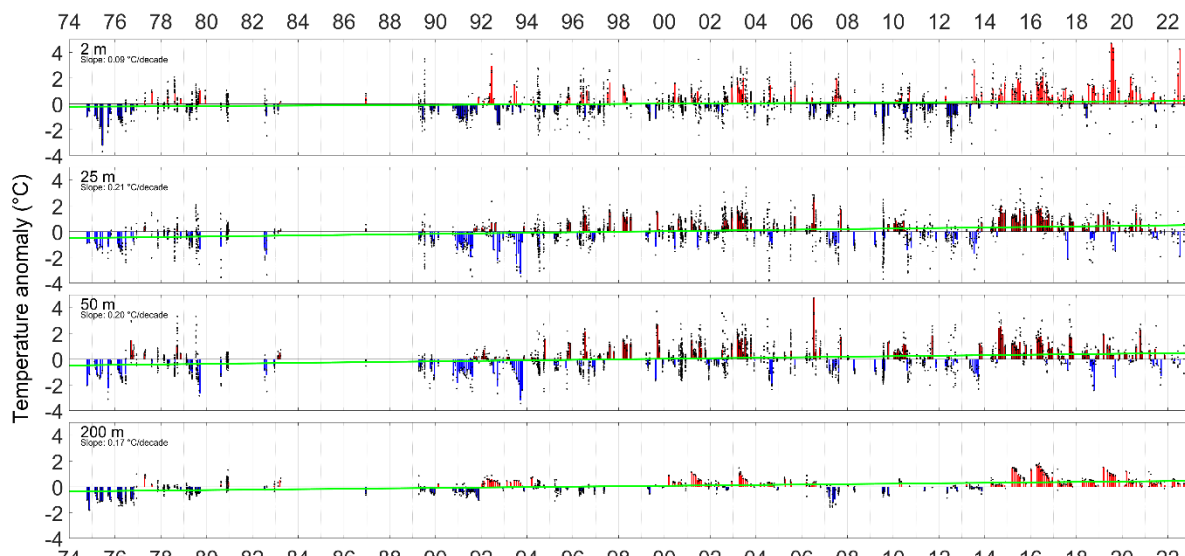


Figure 2. Temperature anomalies in central Prince William Sound (blue shaded area of Fig. 1). Anomalies were calculated with the method of Campbell (2018) Green lines indicate the long-term trend (slope reported on each figure) calculated by least-squares regression.

Phytoplankton productivity

The satellite chlorophyll time series (Fig. 3) shows the standard subarctic annual cycle, with a pronounced spring bloom in April-May, and an occasional autumn bloom in early October.

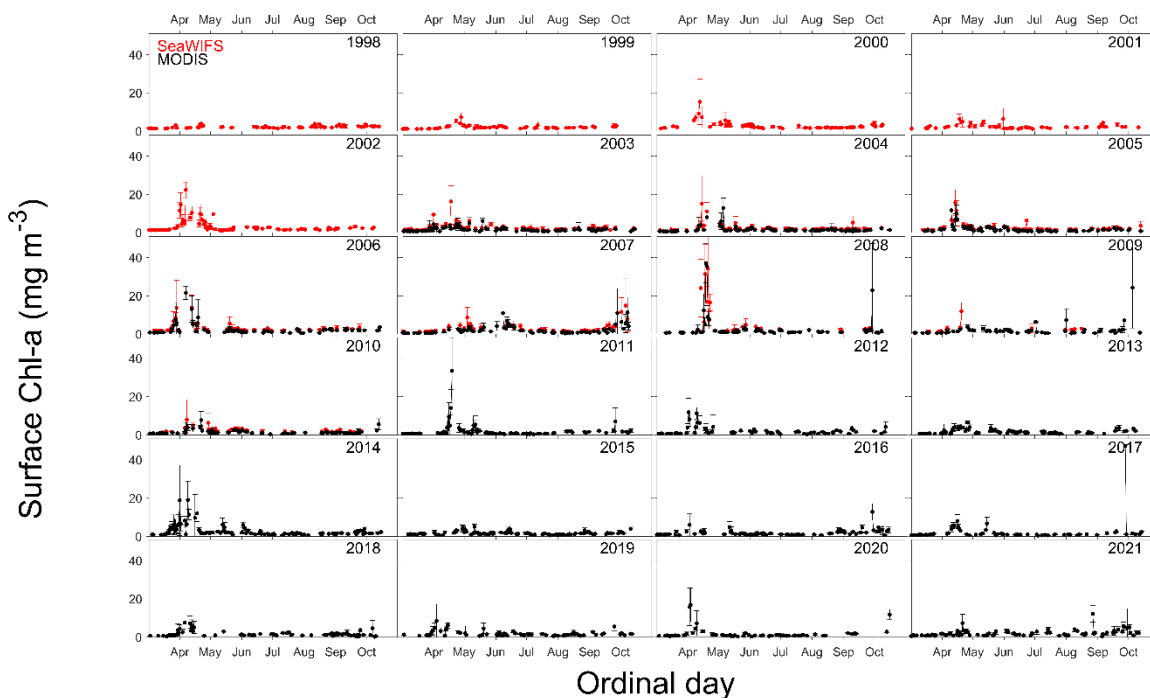


Figure 3. Surface chlorophyll-a time series in central Prince William Sound (PWS). Daily mean and standard deviations within non-cloud-masked pixels in central PWS (inside the green polygon in Fig. 1) are shown. Observations from the sea-viewing wide field-of-view sensor (SeaWiFS) satellite are in red, those from the moderate resolution imaging spectroradiometer (MODIS) satellite are in black.

To examine overall productivity, the observed chlorophyll concentrations were averaged between the MODIS and SeaWiFS datasets to produce a composite time series. The composite time series was then temporally integrated from March 1 to June 1 (with the trapezoid rule). This produces in effect a sum of the total amount of chlorophyll observed by the satellites over the spring bloom time (with a generous temporal margin) and may be considered an index of overall productivity. To examine the potential for phenological shifts in bloom initiation, a simple bloom initiation index was produced by determining the date when chlorophyll concentrations exceeded a threshold value of $2 \mu\text{g/l}$ (other thresholds up to $5 \mu\text{g/l}$ were examined and did not alter the results). The time series of integrated chlorophyll (Fig. 4, top panel) showed a persistent decline in overall productivity over the entire time series, but no trend was observed in the timing of bloom initiation (Fig. 4, bottom panel).

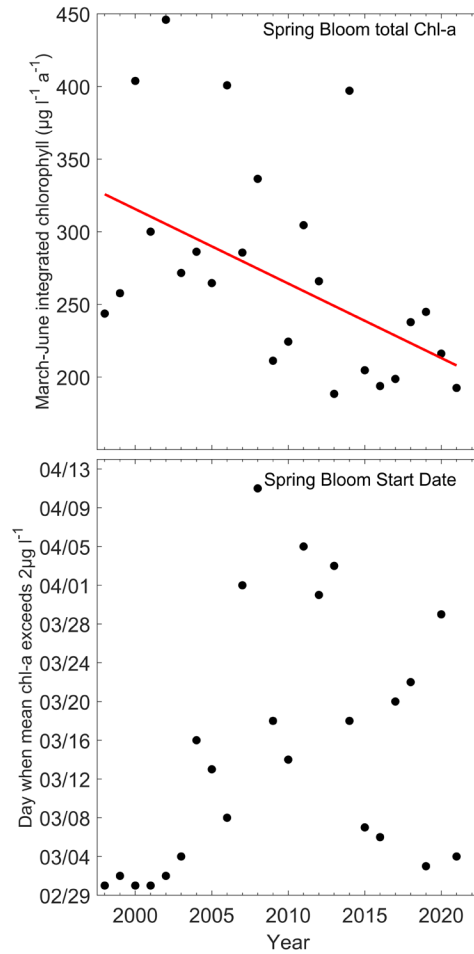


Figure 4. Estimates of the magnitude (top panel) and onset (bottom panel) of the spring bloom in central Prince William Sound (same data as Fig. 3). The magnitude of the bloom was estimated by numerically integrating chlorophyll concentration (Chl-a) from March 1 to June 31 in each year using the trapezoid rule. The onset of the bloom was estimated as the day of the year when surface chlorophyll concentrations first exceeded $2 \mu\text{g/l}$.

Zooplankton composition

Abundance anomalies of all zooplankton species combined did not vary to a great degree over the entire 2009 – 2021 time series (Fig. 5, top panel; note that the y-axis scales vary among panels). Overall zooplankton abundance was well below average in 2021 and appears to have been primarily driven by a decline in cool water taxa (Fig. 5, middle panel). In addition to 2021, there were brief “stanzas” of lower-than-average abundances of cool water taxa in 2016 and 2019. Warm water taxa became more prevalent in the years following the “Blob” heatwave (2014-2017: Fig. 5, bottom panel), and were also more common in late 2019 and late 2020.

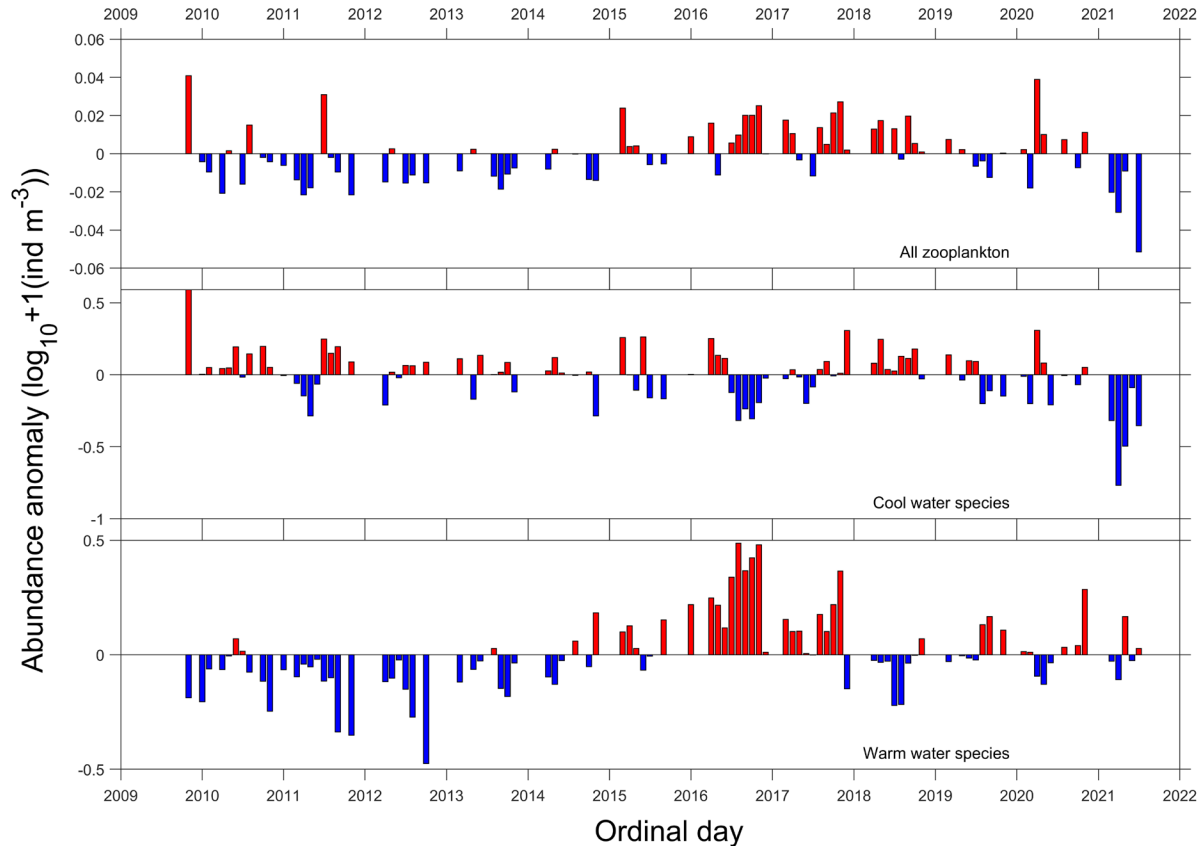


Figure 5. Zooplankton anomaly time series for all species (top panel), cool water species (middle panel), and warm water species (bottom panel). Cool water species are *Neocalanus plumchrus*, *N. flemingeri*, *Acartia longiremis*, *Calanus marshallae*, *Oithona similis*, and *Pseudocalanus sp.* Warm water species are *Calanus pacificus*, *Clausocalanus*, *Corycaeus anglicus*, *Ctenocalanus vanus*, *Mesocalanus tenuicornis*, and *Paracalanus parvus*.

Profiler deployments

The PWS profiler obtains a very high-resolution picture of the evolution of the surface oceanography in PWS; the 2021 deployment is shown in Fig. 6. The onset of thermal stratification occurs in early May and the accumulation of heat throughout the summer months is evident (Fig. 6, top panel). Similarly, the decrease in salinity over the summer months (driven by relaxed wind mixing, precipitation, and ice and snowmelt) is captured (Fig. 6, 3rd panel). The surface and subsurface spring bloom is seen to occur in late April/early May in the chlorophyll-a time series (Fig. 6, 4th panel) along with the concomitant depletion of surface nitrate (Fig. 6, 5th panel). Following the depletion of surface nitrate, a subsurface chlorophyll maximum establishes at the nitricline, which is later disrupted in the autumn months as thermal and salinity stratification breaks down.

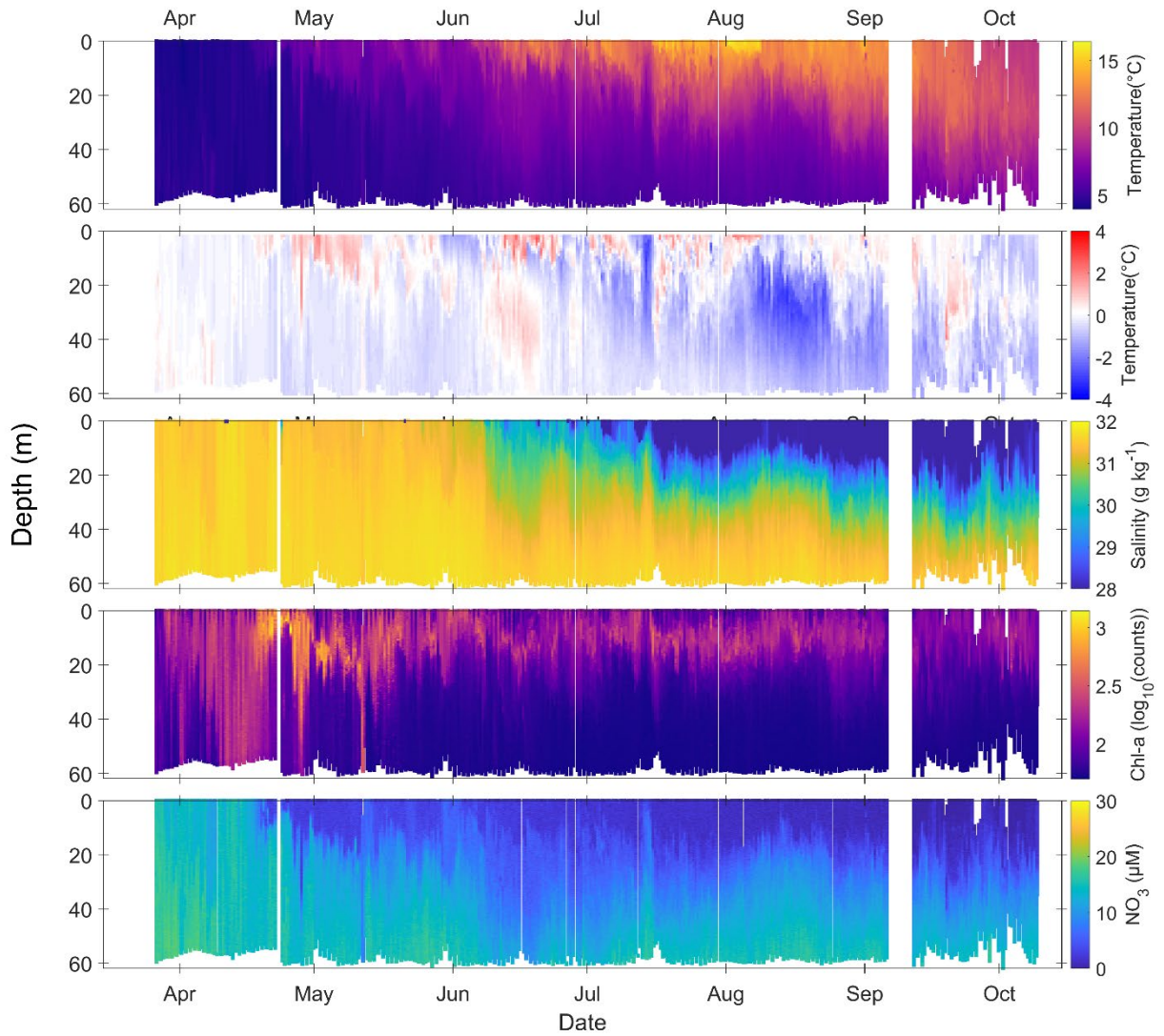


Figure 6. Time series of observations made by the Prince William Sound autonomous profiler in 2021. Top panel: temperature. Second panel: temperature anomaly. Third panel: salinity. Fourth panel: chlorophyll-a (Chl-a), presented as log10 transformed digital counts (counts are linearly proportional to chlorophyll-a concentration). Bottom panel: Nitrate concentration. White spaces are data gaps.

Deployments of the profiler began in 2014, which is when the northern GOA began experiencing its current warm stanza. Although there are not profiler data from before the heatwaves, the Campbell (2018) climatology (zone ‘CS’ in Campbell 2018) was used as the long term average for anomaly calculations (i.e., Fig. 3 of Campbell 2018), and the Campbell (2018) methodology was used to convert the profiler temperature time series to an anomaly time series to examine how the near surface temperature climate in PWS has changed in recent years (Fig. 7). The onset

of warming in early 2014 was captured and persistent surface warm anomalies were present in 2015 through 2017. Near surface temperature anomalies were near climatology in 2018 and were very warm in 2019 (5°C above the long-term average) and into 2020. Near surface temperatures in 2021 were weakly warm, but near the long-term average.

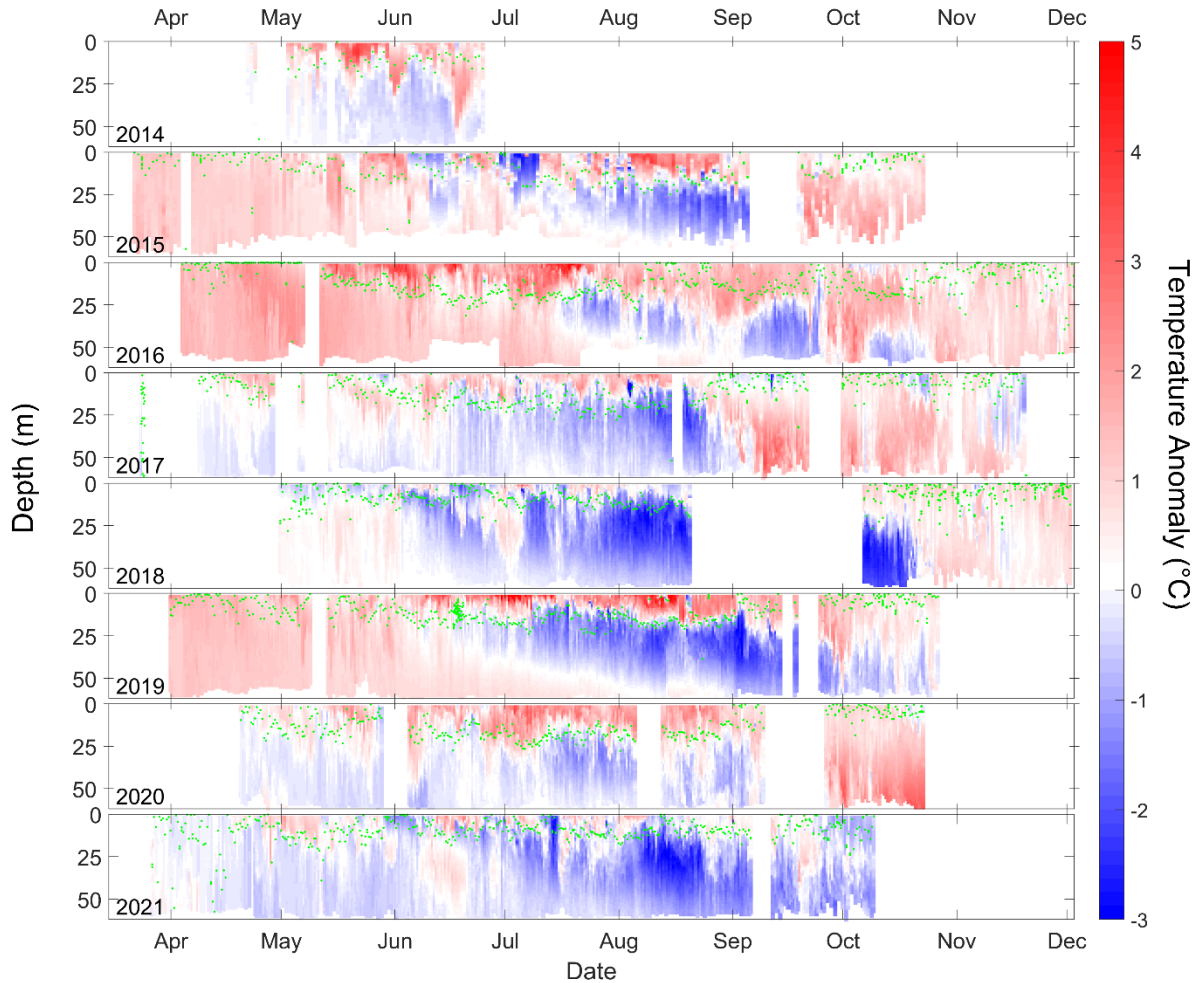


Figure 7. Temperature anomaly time series at the Prince William Sound profiler site, 2014-2020. Temperatures were averaged into 1-m bins and converted into anomalies using the method described in Campbell (2018). Green dots represent the depth of the maximum chlorophyll-a concentration in each profile.

Another persistent trend in the temperature anomalies at the profiler site was a band of below average temperatures below ~25 m depth. Those anomalies likely represent a shoaling of the mixed layer because temperatures at depth tend to be less than those near the surface. The depth of the chlorophyll maximum (which also often coincides with the nitricline: Fig. 6) also often coincided with the interface between the often warmer than average surface layer and the deeper cooler than average layer (Fig. 7, green dots).

The plankton camera aboard the PWS profiler has collected over 4×10^6 images of individual plankters since it was installed on the profiler in 2016. The machine vision system developed to identify the images is described by Campbell et al. (2020; Appendix B) and includes 43 unique taxonomic and functional groups. The plankton assemblage observed by the plankton camera was compared to those captured by nets at similar times and places. Plankton tows were routinely done when servicing the profiler ($n=35$), and net tows at the nearby mid-PWS station occupied during surveys (Fig. 1) were also included if they were done within 4 hours of a profile ($n=15$). Only images with high confidence ($>95\%$ with the confidence filtering method described by Campbell et al. 2020) were used, at the lowest possible taxonomic level (species, if possible, often to genus).

The concentrations of common copepod species estimated by the plankton camera tended to be less than concentrations estimated from collections with the plankton net (Fig. 8, top panel), falling mostly below the 1:1 line. The opposite occurred with more fragile gelatinous taxa (Fig. 8, middle panel), with net-based concentrations tending to be less than those from the camera. There were also several taxa that were only observed by the camera and never in the net samples (the predatory ctenophores *Beroe* and *Bollinopsis*, and Siphonophores). In the other more common taxa (Fig. 8, bottom panel) the observations tended to align along the 1:1 line, albeit with considerable variability (~ 2 orders of magnitude). For all taxa there were numerous instances where one taxon was observed by one method and not at all by the others (the dots along the zero axes in Fig. 8).

One strength of the observations made by the camera is that the approximate depth of each plankter may be inferred from the image timestamp and the pressure-time record from the profiler). To first order, those depth observations will be accurate to approximately ± 5 cm (the camera images a 10 cm x 10 cm area). The results of the classifier may then be used to infer the depth of each identified particle, which has been done for a number of the more common plankton taxa observed in PWS.

Distributions of the common large copepods *Neocalanus* and *Calanus* (Fig. 9, left and center panels) showed maximum abundances during the spring months (April-May), with most individuals observed near-surface, in the top 40 meters. Interannual differences were also apparent. The depth distribution of *Metridia* copepods (Fig. 9, right panels) changed over the course of the year in a consistent fashion, being near-surface in spring, shifting towards deeper depth in early summer (June), and then shifting back to near-surface for the rest of the year. *Metridia* is a known diel migrator, and comparison of daytime and nighttime profiles showed that *Metridia* was mostly observed in the upper 60 m during nighttime (Fig. 10).

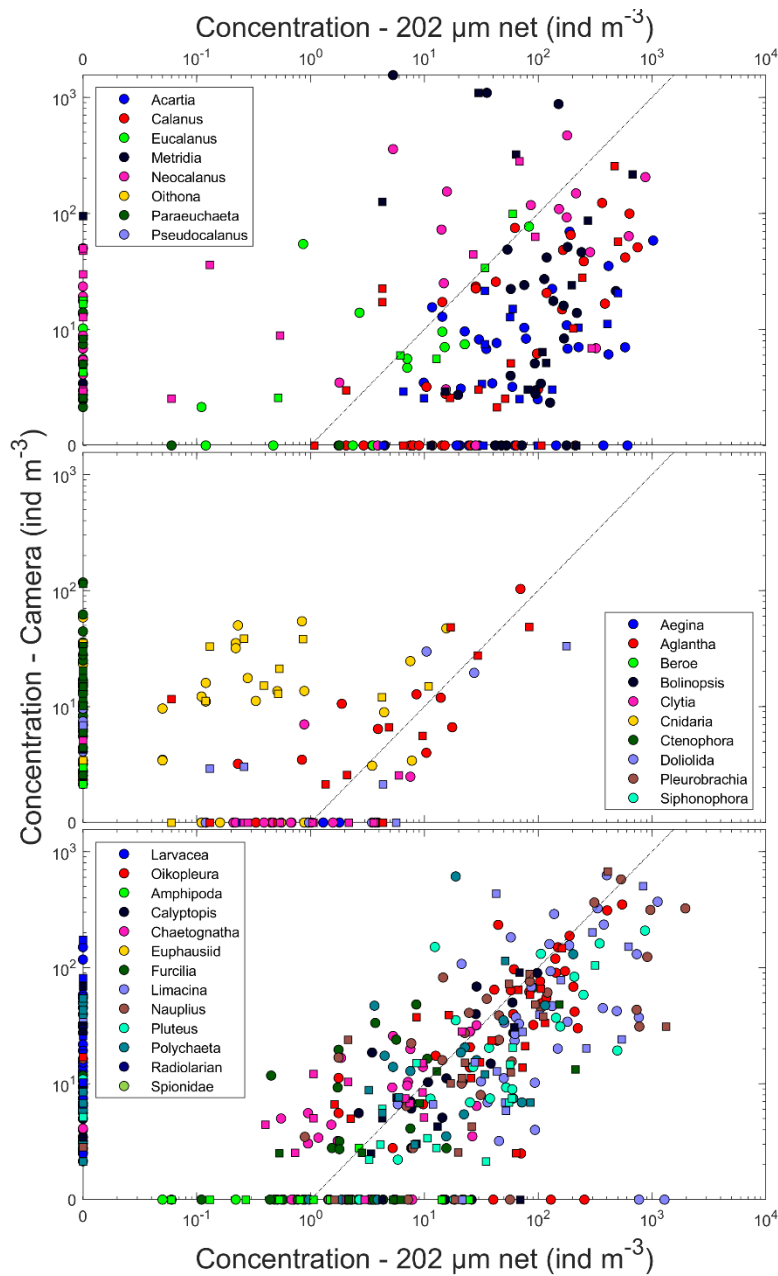


Figure 8. Comparison between concentrations estimated with the camera and from net tows, by taxa. Top panel: common copepod genera; Middle panel: gelatinous taxa; Bottom panel: all other common taxa. Circles are net samples taken at the profiler site, squares are net samples taken at the nearby Prince William Sound station. Instances where a taxon was observed by one method but not the other are along the zero axes.

Distributions of the common small copepods *Pseudocalanus*, *Acartia*, and *Oithona* (Fig. 11) were broadly similar, with broader depth distributions in spring, and being observed in the near-surface layer during the summer months. In some years there was an apparent shift towards

deeper depths in June as was observed in *Metridia*, but the change was less consistent, and did not occur in all years.

Common non-copepod taxa observed by the camera included *Limacina* pteropods, *Oikopleura* larvaceans, and *Pleurobrachia* ctenophores (Fig. 12). Both *Limacina* (Fig. 12, left panels), and *Oikopleura* (Fig. 12, center panels) were common during the spring months, and abundances during the summer months were more variable, with short “blooms” of high abundance lasting two or three weeks. Depth distributions were variable from year-to-year but were often mostly near-surface. The less abundant *Pleurobrachia* (Fig. 12, right panels) was most common in spring and autumn, with occasional short duration increases in the summer months.

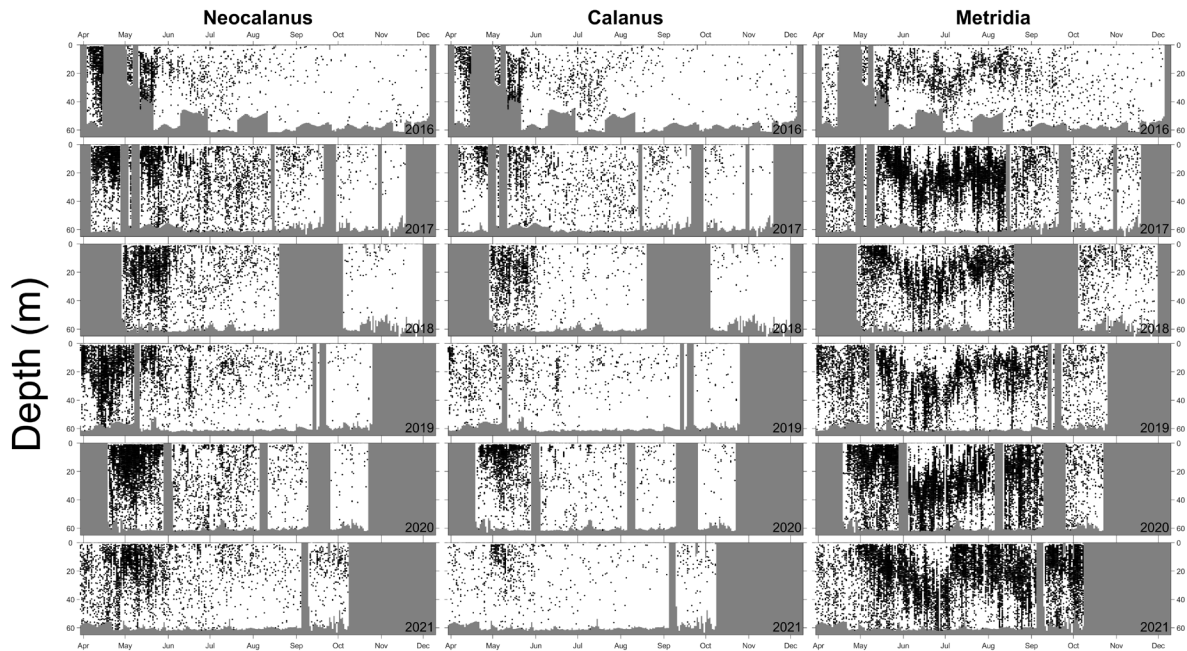


Figure 9. Observations of large copepods at the Prince William Sound profiler site, by depth and time. Each point represents an observation of an individual plankter that was detected by the Campbell et al. (2020) classifier. Rows are deployment years (2016-2021 top-bottom) and columns are *Neocalanus* (left), *Calanus* (center), and *Metridia* (right). Grey areas indicate no data.

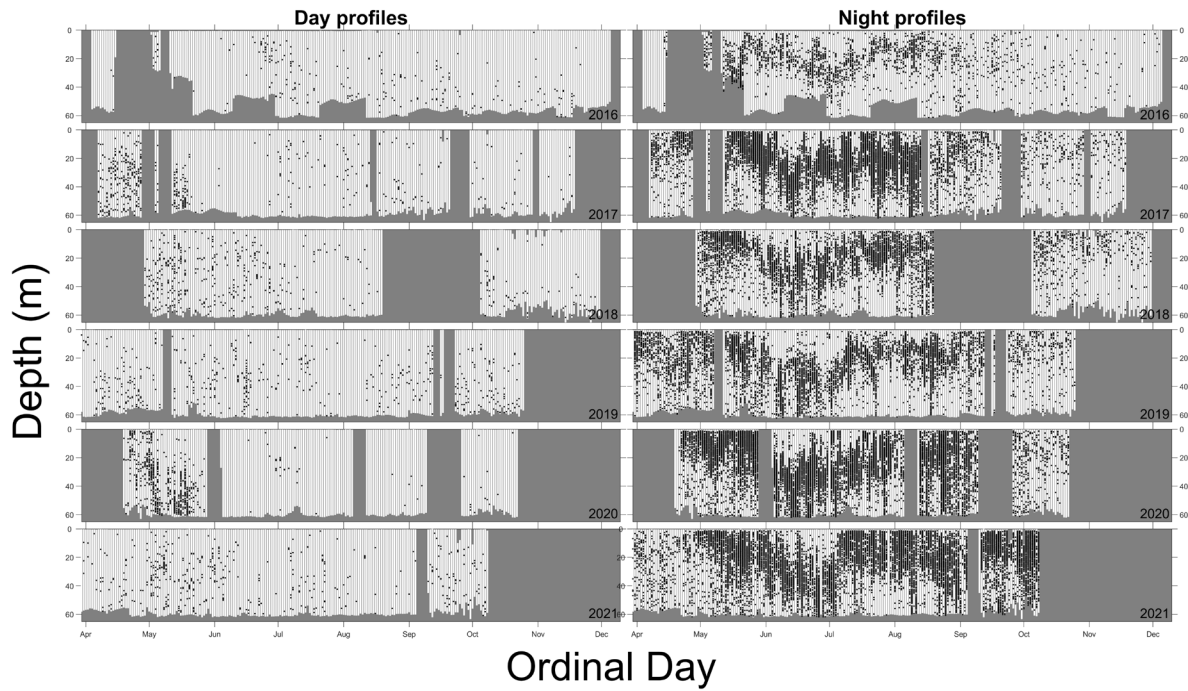


Figure 10. Time-depth distributions of *Metridia* copepods during daytime profiles (left panels) and nighttime profiles (right panels) in Prince William Sound. Grey areas indicate no data.

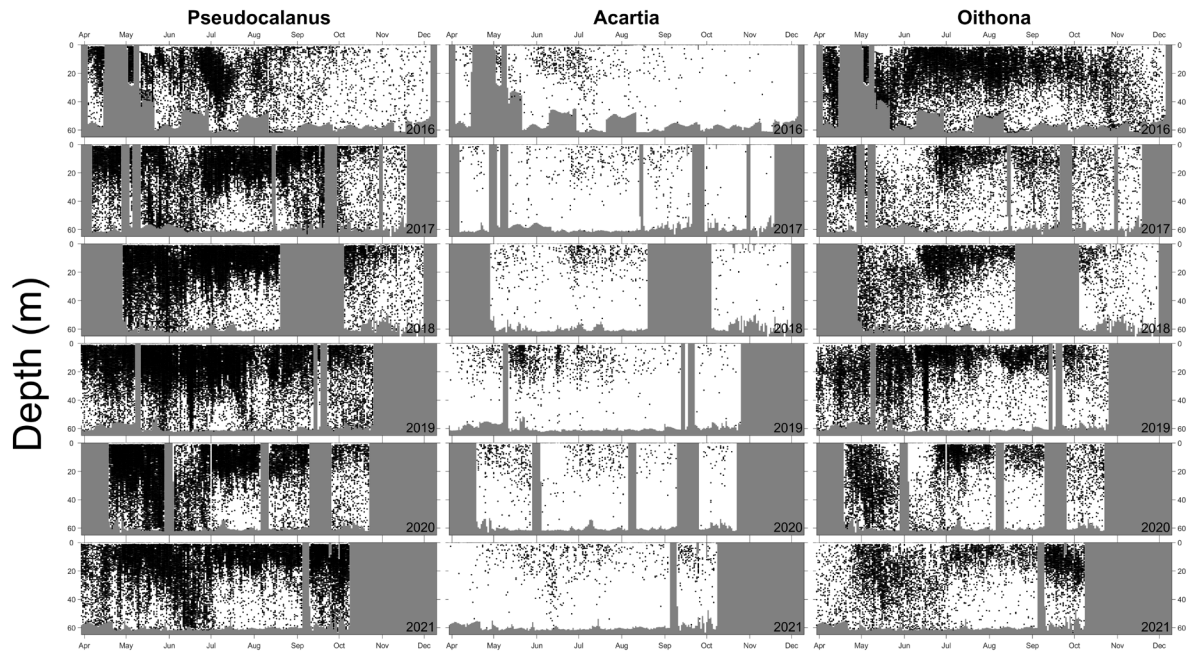


Figure 11. Time-depth distributions of the small copepod species *Pseudocalanus* (left panels), *Acartia* (center panels), and *Oithona* (right panels) in Prince William Sound. Grey areas indicate no data.

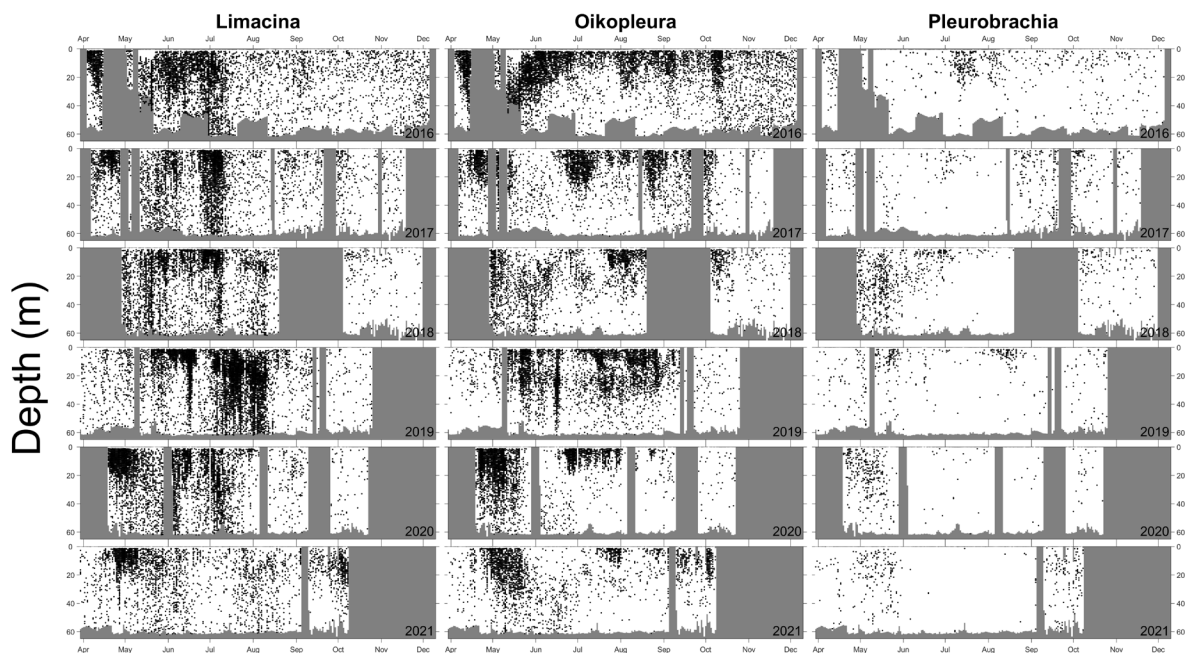


Figure 12. Time-depth distributions of the common non-copepod taxa in Prince William Sound, including *Limačina* (left panels), *Oikopleura* (center panels) and *Pleurobrachia* (right panels). Grey areas indicate no data.

DISCUSSION

The PWS region has for the most part experienced a persistent warming trend over the last 50 years (Fig. 2) similar to coherent warming trends observed throughout the region (Danielson et al. 2022). The exception to that trend has been the northwestern portion of PWS, which is experiencing cooling and freshening near-surface, presumably driven by meltwaters from glaciers of the Chugach and Kenai mountain ranges. There has been a persistent trend towards a shallower mixed layer as well (Campbell 2018; Appendix A, Fig. 7).

Inclusion of data more recent than Campbell (2018) showed that temperatures in central PWS have continued to be above average since late 2013, as have been observed elsewhere in the GOA (see GAK Line, project 21120114-L, and GAK1, project 21120114-I, reports); the period from late 2013 to 2016 having been labelled a basin scale marine heatwave (Bond et al. 2015, Gentemann et al. 2017). Following a weak cooling trend into early 2018 and a brief period of negative anomalies, anomalies again trended warmer than average, reflecting basin-wide increases in sea surface temperature observed in late 2018 and 2019. Near-surface temperature anomalies in 2019 exceeded those observed during the 2013-2016 marine heatwave and appear to be the result of a similar mechanism: a persistent atmospheric ridge (Bond et al. 2015, Amaya

et al. 2020), although the timing of the ridges was quite different. In 2013-2014 the ridge disrupted winter storm tracks and led to reduced mixing of heat out of the surface layer during winter (i.e., “less cooling than usual”). In 2020, a similar ridge led to over a month of calm, sunny weather in July-August that led to enhanced solar heat flux to the surface layer and very high surface layer temperatures (i.e., “more warming than usual”).

The unusually warm temperatures experienced in recent years has caused cascading effects to the members of and productivity by the planktonic food web in PWS. The spring bloom in PWS has not been well described beyond a large-scale satellite-based study (Henson 2007) and a modelling effort done as part of the SEA project (Eslinger et al. 2001); chlorophyll-a and nitrate climatologies do not exist beyond the satellite time series put together for this study (Fig. 3). The canonical picture that emerges (exemplified by 2021 observations; Fig. 6) is that the spring bloom is usually initiated in late April into May, followed by an abrupt decline in early to mid-May when the surface nutrients were exhausted. Phytoplankton biomass remained low (June-September) and concentrated near the nutricline (Figs. 3 and 7) through the summer months. There was occasionally a smaller autumn bloom occurring in early October (Fig. 3) as water column stability broke down and nutrients were mixed upward by equinoctial storms. An autumn bloom either did not occur every year or was sometimes not observed due to cloud cover preventing satellite observations.

Net primary productivity (as estimated by integrating the total amount of surface chlorophyll-a observed via satellite) was variable over the 23-year satellite time series, but it is notable that the lowest amounts yet observed have been since the 2013-14 “Blob” marine heatwave (Fig. 4). Over the entire time series there has been a ~38 % decline in overall productivity. That productivity decline may be related to the continued thinning of the mixed layer in PWS (Campbell 2018; Appendix A, Fig. 7). Annual productivity can be expected to be related to the total amount of nitrate available in the annual surface mixed layer when it is established, since transport between the surface mixed layer and deeper waters is low (Sverdrup 1953): a thinner mixed layer will mean less total nitrate available to primary producers, and less overall productivity. It is possible that some of that deficit might be made up by primary production occurring near the nutricline during the summer months (Figs. 6 and 7), but there is not a long enough time series of observations to test that hypothesis. Although changes in the phenology of phytoplankton blooms have been observed elsewhere (Zhao et al. 2022), episodic acquisition of clear sky satellite imagery of PWS has not allowed definitive detection of such a phenological shift.

Although the time series of zooplankton abundance is the shortest one in this study (13 years), it began well before the marine heatwaves that began in 2013 and gives some idea of pre- and post-heatwave zooplankton assemblages. As was observed in the California Current (Peterson et al. 2017), the assemblage of zooplankton in PWS shifted following the 2013-14 “Blob” heatwave, with taxa representative of warm waters becoming more common, and subarctic species becoming less prevalent (Fig. 8). Although of a higher magnitude (Fig. 2), the 2019 marine

heatwave was of a shorter duration, and appears to have had less impact on the zooplankton assemblage, with smaller, shorter-lived changes. Similar shifts were also observed in the zooplankton sampled in Kachemak Bay / Lower Cook Inlet by project 21120114-J (McKinstry et al. 2022). The recent marine heatwaves have had pervasive effects throughout the higher trophic levels of the GOA ecosystem and have been the focus of other Gulf Watch Alaska projects and studies (projects 21120114-A and 21120114-C: Suryan et al. 2021, Arimitsu et al. 2021).

The PWS profiler provides a very high-resolution temporal picture of the near-surface oceanography of central PWS, and the camera system added in 2016 extends those capabilities to observations of the zooplankton. Most *in situ* camera systems developed to date have been deployed on towed bodies, static moorings, or profiled from ships (Lombard et al. 2021). To this author's knowledge, this is the first and only high frequency profiling deployment of an *in situ* camera at a single site. Given the caveats that camera-based observations may not always be strictly comparable to collections done with nets (Fig. 8), the time series produced by this study provide an unprecedented glimpse into the life histories of some of the more common plankton of PWS.

Observations of the larger copepod species common to PWS match with the phenologies described for them by Cooney et al. (2001b), with *Neocalanus* and *Calanus* occurring primarily in spring and early summer and *Metridia* common later into the year. Smaller copepods do not undergo the annual ontogenic vertical migrations performed/exhibited by large calanoids (Cooney et al. 2001b) and are more prevalent throughout the year. The annual cycles of non-copepod taxa are not well documented, and the distributions presented in Fig. 12 are likely the first of their kind.

The annual cycle of *Metridia* copepods in PWS also is not well described; monthly observations by Cooney et al. (2001b) placed *Metridia* as among the more common species in most spring to autumn months. Depth-specific sampling identified an abundance peak at 150 m depth, with a smaller peak at ~50 m, but it was not specified if the sampling occurred during day or night. *Metridia* sp. are known to undertake large daily vertical migrations (Osgood and Frost 1994), from ~200 m to near surface, and the observations shown here (Fig. 10) also show a migration to near surface. Osgood and Frost (1994) suggested that the diel migration conducted by *M. lucens* might be to avoid visual predators. The shift in the depth ranges of the *Metridia* copepods observed here supports that hypothesis, in that the timing of the depth shift lines up with the annual solar pattern centering on approximately the time of the summer solstice (June 21), when day length is longest and solar insolation at its maximum. It also coincides with a shift in the depth of the chlorophyll maximum, as near surface nitrate became depleted (Figs. 6 and 7). However, the presence of *Metridia* at depths well above the chlorophyll maximum into July and August suggests that the light cue (or lack thereof) at that time may be more important in determining where individuals chose to spend their time.

Zooplankton are the primary link between primary production and higher trophic levels and assessing their abundance in real time is difficult (Weibe and Benfield 2004). The traditional method of sampling with nets and microscopic analysis returns a wealth of taxonomic information at the expense of time; timely information is, however, what is of prime importance to managers. The results of this study show that *in situ* imagery can provide high frequency observations that are of use for both basic research on the lifestyles of numerous plankton taxa, and near-real time assessment of the abundance of ecologically important groups.

CONCLUSIONS

This study described the continued long-term warming trend that has occurred in PWS (and throughout the GOA) over the past several decades. That warming trend is likely responsible for a long-term reduction in overall primary productivity. More recently there have been a number of marine heatwaves which have altered marine ecosystems in PWS and beyond, including shifts in the zooplankton community that have cascaded upward through the food web (Arimitsu et al., 2021; Suryan et al. 2021). A high frequency profiling mooring was used to examine the mechanisms behind those changes and shows promise as a method for the rapid assessment of plankton populations.

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APPENDIX A

See separate PDF.

APPENDIX B

See separate PDF.