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

Long-term Monitoring of Oceanographic Conditions in the Alaska Coastal Current from Hydrographic Station GAK-1

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

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Study History: Hydrographic sampling at oceanography station GAK-1 began in December 1970. For the first 20 years, sampling was accomplished by ships-of-opportunity, primarily research vessels as they left or entered the port of Seward, so the time interval varied from several times per month to several times per year. Since September 1990 the sampling has been accomplished nominally monthly, usually as a single CTD (conductivity-temperature-depth) profile to within 10 m of the bottom (263 m). The location is 59° 50.7' N, 149° 28.0' W and is located within the Alaska Coastal Current, so it is well "connected" with the shelf circulation and the upstream outflow from Prince William Sound.

Samples taken between September 1990 and 1996 were sponsored by the National Oceanic and Atmospheric Administration's Office of Global Programs (Office of Ocean and Earth Sciences, Ocean Observing Division, Observing Networks Branch) and thereafter by the *Exxon Valdez* Oil Spill Trustee Council. Since 1997, sampling has been enhanced by regular occupations of the Seward Line, supported by the National Oceanic and Atmospheric Administration and the National Science Foundation through the Global Oceans Ecosystem Dynamics program over 1997-2004 and since 2005 by the Alaska Ocean Observing System, the North Pacific Research Board, and the Gulf Watch Alaska program. The National Science Foundation's Northern Gulf of Alaska Long Term Ecological Research program added a summer occupation beginning in 2018.

In 1998, a subsurface taut-wire mooring was added to the GAK-1 program to collect temporally high-resolution hydrographic data at up to seven discrete depths through the water column. The monthly CTD casts and the mooring provide cross-platform redundancy for each other to maintain time series integrity in the event of a loss of the mooring, instrumentation failure, or interruptions in the CTD sampling.

The GAK-1 time series was initiated by Dr. Thomas Royer of the University of Alaska Fairbanks, and University of Alaska Fairbanks faculty have maintained this sampling ever since. Oversight of the effort transitioned in the mid-1990s to Dr. Thomas Weingartner, who subsequently led the program until 2017, when leadership shifted to Dr. Seth Danielson. GAK-1 data has been used within at least fifteen graduate student master's theses and doctoral dissertations. Over 100 peer-reviewed publications have employed data collected at station GAK-1 (see http://research.cfos.uaf.edu/gak1/ for a full listing); since 2010 the citation list has grown by nearly five publications per year. These include peer-reviewed journal articles and resource management agency reports. The topics covered by publications using data collected at

GAK-1 range from physical, chemical, and biological oceanography to paleoclimate studies, fisheries research and management, and ecosystem-based management applications.

Abstract: The oceanographic station GAK-1 hydrographic times series provides a reference temperature and salinity dataset for the northern Gulf of Alaska continental shelf over 1970-2022. Located near the mouth of Resurrection Bay, measurements extend 250 m from the surface to just above the seafloor. Conductivity-temperature-depth sampling is accomplished with nominally monthly ship-based profiles and time series dataloggers that are affixed to an annually serviced oceanographic mooring. The GAK-1 dataset documents the magnitude of thermohaline environmental change experienced by the Gulf of Alaska marine ecosystem. Assessments of temporal-spatial variability demonstrate that the GAK-1 site provides measurements that are well representative of the regional shelf. Record-length trends of temperature and salinity drive the system towards enhanced stratification, with warming greater at the surface (0.22 °C $decade^{-1}$) than near the seafloor (0.16 °C $decade^{-1}$), freshening at the surface (-0.056 $decade^{-1}$), and salinization near the seafloor (0.037 $decade^{-1}$). Analysis of seasonality reveals largest salinity anomalies in late summer and fall months, while largest thermal anomalies tend to occur in winter and spring. The value of this data record is demonstrated through the more than 100 peer-reviewed journal articles, graduate theses and dissertations, and management agency reports that utilize data collected at GAK-1.

Key words: Alaska Coastal Current, climate change, Gulf of Alaska, hydrography, North Pacific, Resurrection Bay, salinity, Seward Line, temperature

Project Data: Project data are a combination of time series collected by conductivity-temperature-depth (CTD) dataloggers mounted to an oceanographic mooring at station GAK-1 and hydrographic profiles collected from a ship-lowered CTD profiler. Data are archived in human-readable ASCII files. No limitations or restrictions are placed on these data.

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.

Data can be accessed via the following archives.

Danielson, S. L. 2022. GAK1 mooring data via the Alaska Ocean Observing System Gulf of Alaska data portal. https://portal.aoos.org/#metadata/103522/station/data

Danielson, S. L. 2021. CTD profile time series data from the GAK1 site in the Northern Gulf of Alaska, 1970-2020 (Data One Gulf Watch Environmental Drivers Component). 10.24431/rw1k595, version: 10.24431_rw1k595_20210618T011621Z.

Danielson, S. L., and T.J. Weingartner. 2021. Temperature and Salinity Timeseries data from the GAK1 Mooring, Seward, AK, 1998-2017 (Data One Gulf Watch Alaska Environmental Drivers Component). Research Workspace. doi:10.24431/rw1k32q, version: 10.24431_rw1k32q_20210303T210210Z.

Citation:

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TABLE OF CONTENTS

LIST OF FIGURES

Long-term Monitoring of Oceanographic Conditions in the Alaska Coastal Current from Hydrographic Station GAK-1

EXECUTIVE SUMMARY

The oceanographic station GAK-1 hydrographic times series provides a reference temperature and salinity dataset for the northern Gulf of Alaska over 1970-2022. The goal of this program is to provide high quality, long-term thermohaline data that resolve variations occurring over short (hours to days) to long (inter-annual to multi-decadal) periods on the Gulf of Alaska shelf, including in the area affected by the *Exxon Valdez* oil spill. The GAK-1 dataset documents the magnitude of environmental change experienced by the Gulf of Alaska marine ecosystem and provides the broader temporal and spatial perspective important to our ecosystem-level understanding and management of the northern Gulf of Alaska. We measure temperature and salinity throughout the water column; near-surface pressure fluctuations; water column stratification; and chlorophyll a fluorescence as a proxy of phytoplankton concentration.

Hydrographic sampling at oceanography station GAK-1 began in December 1970. For the first 20 years, sampling was accomplished by ships-of-opportunity, primarily research vessels as they left or entered the port of Seward, so the time interval varied from several times per month to several times per year. Since September 1990 the sampling has been accomplished nominally monthly, usually as a single CTD (conductivity-temperature-depth) profile to within 10 m of the bottom (263 m). The location is 59° 50.7' N, 149° 28.0' W and resides within the Alaska Coastal Current, so it is well "connected" with the shelf circulation and the upstream outflow from Prince William Sound. In 1998, a subsurface taut-wire mooring was added to the GAK-1 program to collect temporally high-resolution hydrographic data at up to seven discrete depths through the water column. The monthly CTD casts and the mooring provide cross-platform redundancy for each other, maintaining time series integrity in the event of a loss of the mooring, instrumentation failure, or weather interruptions in the CTD sampling.

The value of the GAK-1 dataset is demonstrated through the steady and increasing number of publications that apply it to new scientific studies. Over 100 publications employ data collected at station GAK-1; since 2010 the citation list has grown by nearly five publications per year. These include peer-reviewed journal articles, graduate student theses and dissertations, and resource management agency reports. The topics covered by publications using data collected at GAK-1 range from physical, chemical, and biological oceanography to paleoclimate studies, fisheries research and management, and ecosystem-based management applications.

Assessments of spatial and temporal thermal variability demonstrate that the GAK-1 site provides measurements that are well representative of the regional shelf. Record-length trends of temperature and salinity drive the system towards enhanced stratification, with warming greater at the surface (0.22 °C decade^{-1}) than near the seafloor (0.16 °C decade^{-1}), freshening at the surface (-0.056 decade^{-1}), and salinization near the seafloor (0.037 decade^{-1}). Analysis of

seasonality reveals largest salinity anomalies in late summer and fall months, while largest thermal anomalies tend to occur in winter and spring.

The GAK-1 dataset is being used by scientists to improve our ability to numerically hindcast and forecast oceanic conditions in the Gulf of Alaska. GAK-1 data was used to independently tune and validate results from coupled high-resolution terrestrial and oceanographic circulation models and show meaningful improvements in the model's ability to estimate the Gulf of Alaska salinity and salinity gradients. The developed methodology and additional model validations, in turn, were subsequently applied to the modeling of Gulf of Alaska ocean acidification.

The GAK-1 dataset is also regularly employed by academic and agency publications that focus on fisheries management. For example, it is annually incorporated into the National Oceanic and Atmospheric Administration Ecosystem Status Report for the Gulf of Alaska. A series of peer-review publications have used GAK-1 as a baseline environmental dataset used for assessing ecological impacts of climate change, with a particular focus on appropriate statistical techniques given that many ecological relationships have potential to preclude an accurate application of standard statistical tests that assume temporally stationary relationships. Other studies with management applications of the GAK-1 data include studies that examine humpback whale depredation; chum salmon size, condition, and abundance; Pacific cod spawning during a Gulf of Alaska heatwave; walleye pollock eggs contributions to the Gulf of Alaska spring food web; and golden king crab size at maturity.

INTRODUCTION

The Ecosystem Drivers component of the *Exxon Valdez* Oil Spill Trustee Council-funded Gulf Watch Alaska program documents environmental conditions in the spill-affected area and assesses how these conditions impact the study region's ecosystem. The ecosystem is complex and mostly unviewable by direct means due to its sub-surface location and the microscopic size of most marine organisms. This leads to apply both traditional (e.g., net tows, water chemistry analyses) and modern high-technology approaches (e.g., underwater uncrewed vehicles, oceanographic moorings) in our pursuit of achieving a thorough understanding of the Gulf of Alaska's (GOA's) ecosystem state and functioning (Fig. 1).

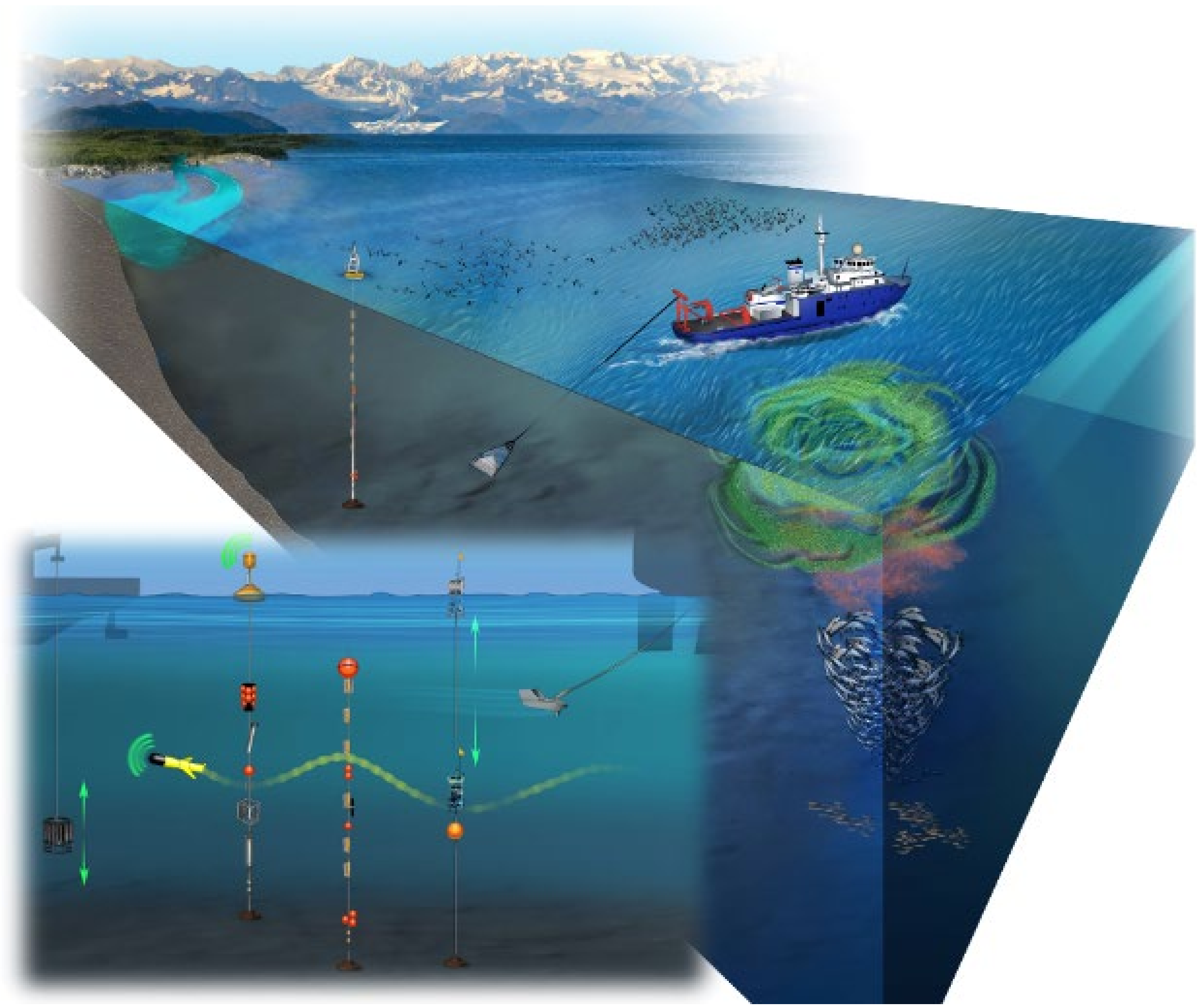

Figure 1. Artist's rendition of key Gulf of Alaska marine ecosystem components and measurement tools and techniques. Ecosystem components shown include seabirds, fishes, phytoplankton blooms, zooplankton aggregations, glacially fed fresh coastal river discharge and a buoyant, low-salinity coastal current, and oceanic fronts, waves, and stratification. Measurement tools include ships, towed and lowered nets and electronic sensor packages, uncrewed underwater autonomous vehicles, meteorological buoys, and oceanographic moorings.

During the 2017-2021 Gulf Watch Alaska funding cycle, scientists from four of the Environmental Drivers component projects (GAK-1, Cook Inlet, Prince William Sound, Seward Line) and the Nearshore component collectively analyzed surface and subsurface temperature data from across the Gulf of Alaska, resulting in a peer-reviewed synthetic study (Danielson et al. 2022) that aggregated data from a across a broad suite of measurement platforms. The study highlighted the GAK-1 record as a centrally located (Fig. 2) and temporally long *in situ* reference dataset that provided a special anchor for assessing spatial and temporal variations across the study region. Danielson et al. (2022) focused on long-term trends and horizontal and vertical spatial structure of thermal variability in time.

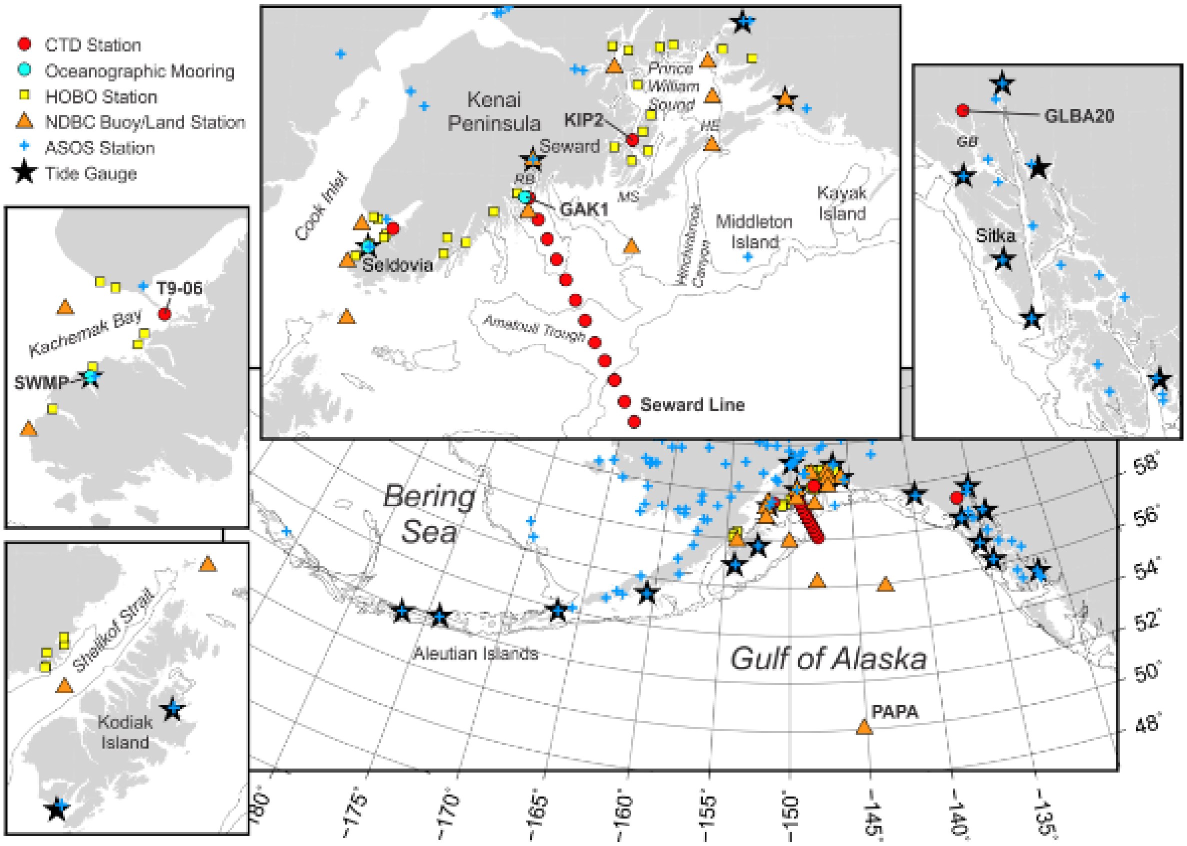

Figure 2. Study region maps showing place names and station locations, including GAK-1 and System Wide Monitoring Program (SWMP) moorings (cyan circles), buoys and land stations (orange triangles), tide gauge stations (black stars), weather stations (blue plus symbols), intertidal HOBO data loggers (yellow squares), and conductivity-temperature-depth stations (red circles). See Table S1 for station coordinates, data temporal coverage, and site characteristics. Abbreviations include: RB = Resurrection Bay; GB = Glacier Bay; HE = Hinchinbrook Entrance; MS = Montague Strait. Bathymetric contours are drawn at 180 and 1000 m depths. Reproduced from Danielson et al. (2022).

The GAK-1 dataset is collected under the fundamental notion that oceanic conditions are important to the physical and biological functioning of the Prince William Sound and GOA ecosystems. To that end, many dozens of papers have examined this hypothesis from numerous perspectives. As the chemical and biological datasets mature (in terms of quality of resolution, duration, and frequency), we expect that the insights gleaned through interdisciplinary analyses will grow in kind.

The 52-year GAK-1 time series has helped show:

- Large interannual differences associated with El Nino and La Nina events, including substantial differences in the spring bloom between these phenomena (Weingartner et al. 2005, Childers et al. 2005).
- The intimate connection between coastal freshwater discharge and the depth-varying evolution of winter and spring temperatures over the shelf (Janout et al. 2010, 2013).
- That GAK-1 provides a reliable index of Alaska Coastal Current (ACC) transports of mass, heat, and freshwater and that near-surface salinities are correlated with coastal freshwater discharge from around the Gulf (Weingartner et al. 2005).
- Variations in mixed-layer depth in the northern GOA, which affect primary production (Sarkar et al. 2006).
- Decadal scale trends in salinity and temperature, (Royer 2005, Royer and Grosch 2006, Weingartner et al. 2005, Janout et al. 2010, Kelley, 2015) and a decoupling of near-surface and near-bottom waters through increased stratification (Kelley 2015) with implications for nutrient resupply to the euphotic zone and long-term changes in shelf productivity.
- The relationships between temperature and salinity variations and the Pacific Decadal Oscillation and the strength and position of the Aleutian Low (Royer 2005, Weingartner et al. 2005, Janout et al. 2010).
- That the record can guide understanding the variability in iron concentrations, a potentially limiting micro-nutrient required by many phytoplankton. Preliminary efforts indicate that iron and surface salinity are correlated at least in certain seasons (Wu et al. 2008).
- Between about 1000 and 1500 years before present, the northern GOA likely experienced a cooler, more sluggish and higher salinity ACC, whereas between 600 and 1000 years before present a stronger Aleutian Low may have driven a stronger and fresher ACC (Hallmann et al. 2011).
- Ocean acidification (carbonate) system variability can be described using multiple linear regression models to predict dissolved inorganic carbon and total alkalinity using observations of nitrate, temperature, salinity, and pressure (Evans et al. 2013).
- Environmental influences on red king crab (Bechtol 2009), salmon (Boldt and Haldorson 2002, Eggers et al. 2013, Munro and Tide 2014), rock sole (Fedewa et al. 2015), spiny dogfish (Trbuzio 2009).
- As shown and discussed by Mueter et al. (1994), Eslinger et al. (2001), Mueter (2004), and Spies (2007), environmental conditions monitored at GAK-1 affect and relate to many ecosystem processes on both the shelf and within Prince William Sound and Lower Cook Inlet/Kachemak Bay.

In addition to the studies and temperature-focused synthesis noted above, the GAK-1 dataset is used in a variety of other synthetic analyses, manuscripts, and products during this past funding cycle (2017-2021), including the following applications.

The GAK-1 data provided a 48-year baseline to a study of ecological effects following the 2014-2016 Pacific Marine Heatwave (Suryan et al. 2021). Suryan et al. (2021) documented persistence in ecological impacts following the 2014-2016 Pacific Marine Heatwave. A high-resolution modeling study demonstrated the value of coupled terrestrial-ocean circulation models and the numerical hindcast fidelity of a 3-D ocean circulation model in being able to reproduce coastal haline anomalies observed at station GAK-1 (Danielson et al. 2020). The developed methodology and additional model validations, in turn, were subsequently applied to the modeling of GOA ocean acidification (Hauri et al. 2020, 2021). As part of a study from the Gulf Watch Alaska EVOSTC-funded Continuous Plankton Recorder project within the Environmental Drivers, the GAK-1 dataset provided a reference for thermal conditions in the GOA for a study examining variability of lower trophic levels on the GOA shelf (Batten et al. 2018).

The Northern Gulf of Alaska (NGA) Long-term Ecological Research (LTER) program now highlights the GAK-1 dataset as a key "signature dataset", in which near-surface (Fig. 3) and near-bottom aggregated time series are provided in a compact and user-friendly format. This value-added compilation is available at the NGA LTER website and is making the GAK-1 dataset even more accessible to stakeholders, including other academic and agency scientists. The NGA LTER group directs outreach focus to K-12 and undergraduate students and utilizes this dataset to foster exciting student-led explorations of real data, such as through the Alaska Data for Undergraduate Educational Modules (AKDaTUM) program.

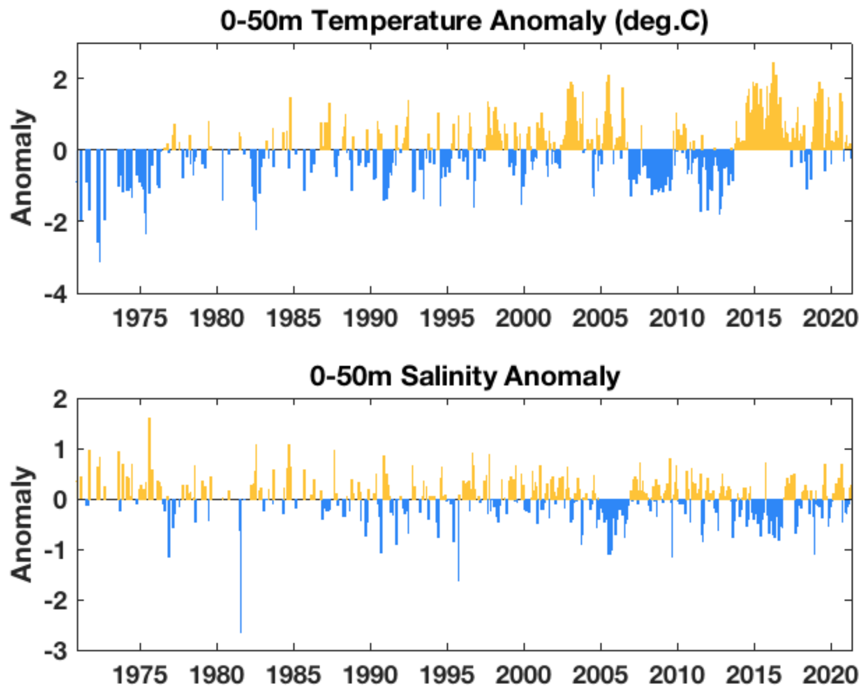

Figure 3.Example visualization of a GAK-1 derivative data product provided in partnership between Gulf Watch Alaska and the Northern Gulf of Alaska Long Term Ecological Research program.

The GAK-1 dataset is also regularly used within academic and agency publications that focus on fisheries management. For example, it is annually incorporated into the National Oceanic and Atmospheric Administration (NOAA) Ecosystem Status Report for the GOA (e.g., Ferriss and Zador 2021), a state-of-the-marine-ecosystem report that informs the North Pacific Fisheries Management Council (NPFMC) as it considers and sets harvest levels. A series of recent peer-review publications uses GAK-1 as a baseline environmental dataset for assessing ecological impacts of climate change (Litzow et al. 2022), with a particular focus on identifying appropriate statistical techniques used in ecological modeling applications, given that many ecological relationships are nonstationary and thus have potential to preclude an accurate application of standard statistical approaches (e.g., Litzow et al. 2020a, 2020b). Other studies with management applications using the GAK-1 data include those that examine humpback whale depredation (Chenoweth and Criddle 2019); chum salmon size, condition, and abundance (Kohan et al. 2017); pacific cod spawning during a GOA heatwave (Laurel and Rogers 2020); walleye pollock egg contributions to the GOA spring food web (Nielsen et al. 2019); and golden king crab size at maturity (Olson et al. 2018).

The value of the GAK-1 dataset is demonstrated through the steadily increasing number of publications that apply it to new scientific studies. Over 100 publications employ data collected at station GAK-1; since 2010 the citation list has grown by nearly five publications per year.

OBJECTIVES

The goal of this program is to provide high quality, long-term data to quantify and understand variations that occur over short (hours to days) to long (inter-annual to multi-decadal) periods on the GOA shelf. This measurement provides the broader temporal and spatial perspective important to our ecosystem-level understanding and management of the northern GOA. Specifically, we measure:

- Temperature and salinity throughout the water column
- Near-surface pressure fluctuations
- Water column stratification since this affects phytoplankton bloom dynamics
- Fluorescence at 20 m depth as a measure of phytoplankton standing crop

METHODS

Study Area

The GAK-1 hydrographic station is located at the mouth of Resurrection Bay (Figs. 2, 4), within the low-salinity core of the ACC midway between Prince William Sound and Cook Inlet, at 59° 51'N, 149° 28'W and in approximately 272 m water depth. The nearby GAK-1 mooring is located at 59° 51.2' N, 149° 30.0' W in approximately 265 m water depth. GAK-1 is the inner-most (most coastal) station of the Seward Line transect.

Figure 4. View from GAK-1 to Bear Glacier in north (top, December) and to the Chiswell Islands in the south (bottom, July). Photographs by S. Danielson.

Sample Collection Methods

Over 2017-2021, nominally monthly CTD casts were conducted from six vessels: *R/V Little Dipper, R/V Nanuq, R/V Sikuliaq, R/V Tiglax, M/V Dora,* and *M/V Acorn*. In July 2017, our primary sampling vessel, the University of Alaska Fairbanks' (UAF's) 28-ft single-engine *R/V Little Dipper*, suffered an engine failure. Using funds available to UAF's College of Fisheries and Ocean Sciences we assembled a bid package for the design and construction of a replacement coastal research vessel and in summer UAF took delivery of the 41-ft dual-engine *R/V Nanuq*.

May, July, and September GAK-1 profiles are collected using the EVOSTC-funded Seward Line program's occupation of the GAK-1 station (typically aboard *R/V Sikuliaq* and *R/V Tiglax*). The monthly CTD casts are collected by using a portable CTD (Sea-Bird SBE-25+V2) aboard *R/V Nanuq* and chartered fishing vessels, or by using a Sea-Bird SBE-9/11 CTD while aboard *R/V Sikuliaq* and *R/V Tiglax*.

CTD data represent the fundamental physical hydrographic measurements, and our data are fully comparable to all other high-quality CTD profile and time-series data from around the globe, including autonomous profiling float data from the Argo program in the deep North Pacific, Seward Line program hydrography, and hydrography from other federally and international supported oceanographic research programs. The chosen Sea-Bird Electronics instruments represent this manufacturer's industry-leading CTD sensors that are well known for their accuracy, stability, and low sensor drift. With a sample rate of one per month for the CTD profiles we well capture seasonal-scale hydrographic anomalies, and with the 15-minute MicroCAT sampling we resolve signals associated with storms, tides, and other episodic and high frequency phenomena.

Following past GAK-1 protocols, we acquire nominally monthly CTD measurements and year-long, continuous measurements from a subsurface mooring with temperature and conductivity (T/C) recorders placed at water depths of 20, 30, 60, 100, 150, 200, and 250 m. A fluorometer (Wetlabs, Inc.) is included at 20 m depth to determine timing and duration of spring, summer, and fall blooms. The fluorometer emits an illuminated beam of light (at 470 nm) that stimulates chlorophyll in the beam path. The absorbed light excites the chlorophyll molecules, which emit light (fluoresce) at 695 nm. The emitted light is detected by the fluorometer, and the intensity of the fluorescence is roughly proportional to chlorophyll biomass. Fluorescence is a relative measure of chlorophyll concentration, and the signal has dependencies on temperature, phytoplankton species composition, and health of the algae cells.

The moored T/C recorders (Fig. 5) are Sea-Bird SBE-37 MicroCats (at depths greater than 20 m). At 20 m depth we have deployed a SeaCAT with an attached fluorometer or another MicroCAT with a stand-alone fluorometer datalogger. Sea-Bird performs pre- and post-deployment calibrations for the moored and profiling instrumentation, upon which we determine sensor drift (typically ~0.01°C yr^{-1} and ~0.03, or better, Practical Salinity Unit yr^{-1}). The SBE-25 and SBE-9/11 profilers' sensors have an accuracy ~0.01 or better for salinity and 0.005 °C for temperature. The mooring is recovered and re-deployed annually. Biofouling gradually degrades the signal quality of the fluorometer, so we strive to deploy the mooring in March or early April (depending upon weather) in order to minimize fouling potential prior to the spring bloom in April or May. Temperature and salinity data are sampled at 15-minute intervals, except at 20 m depth where power supply considerations for the optics dictate hourly sampling.

The moored instruments and monthly CTD sampling schemes are complementary; the CTD provides high vertical resolution at monthly time scales and the mooring provides high temporal resolution, but at coarser vertical spacing. The monthly CTDs provide redundancy in the event of mooring loss or instrument failure on the mooring. The GAK-1 monthly temperature and salinity are statistically significant predictors of monthly anomalies of the along-shelf baroclinic transport in the ACC, so ACC transport anomalies are monitored indirectly from the GAK-1 data (Weingartner et al. 2005).

Data processing and analysis

Data are processed using the CTD manufacturer's software (Sea-Bird Electronics, Inc.; Seasoft V2: SBE Data Processing, Version 7.21k) and the MATLAB scientific computing software suite (Mathworks, Inc.)

We compute standard statistical metrics (mean, standard deviation, anomalies) for each month and depth and compare these with historical data since the thrust of this effort is to quantify seasonal to interannual and longer variability. We incorporate integrated discharge estimates (Beamer et al. 2016) and estimates of air-sea heat fluxes derived from National Center for Environmental Prediction (NCEP) in our analyses of salinity and temperature variability.

We quantify spring and summer phytoplankton blooms in relation to changes in stratification, runoff, and winds. Stratification estimates are made from the three uppermost mooring instruments and the monthly CTD surveys. The fluorescence data provide an estimate of the number of blooms and bloom duration observed in spring and summer. This approach is necessarily subjective since a bloom event is defined with reference to a baseline, which may drift over time because of biofouling, and because phytoplankton species composition affects fluorometer signals. However, when present, biofouling develops after the spring bloom, so our qualitative descriptions are primarily valuable in describing year-to-year variability of the spring bloom.

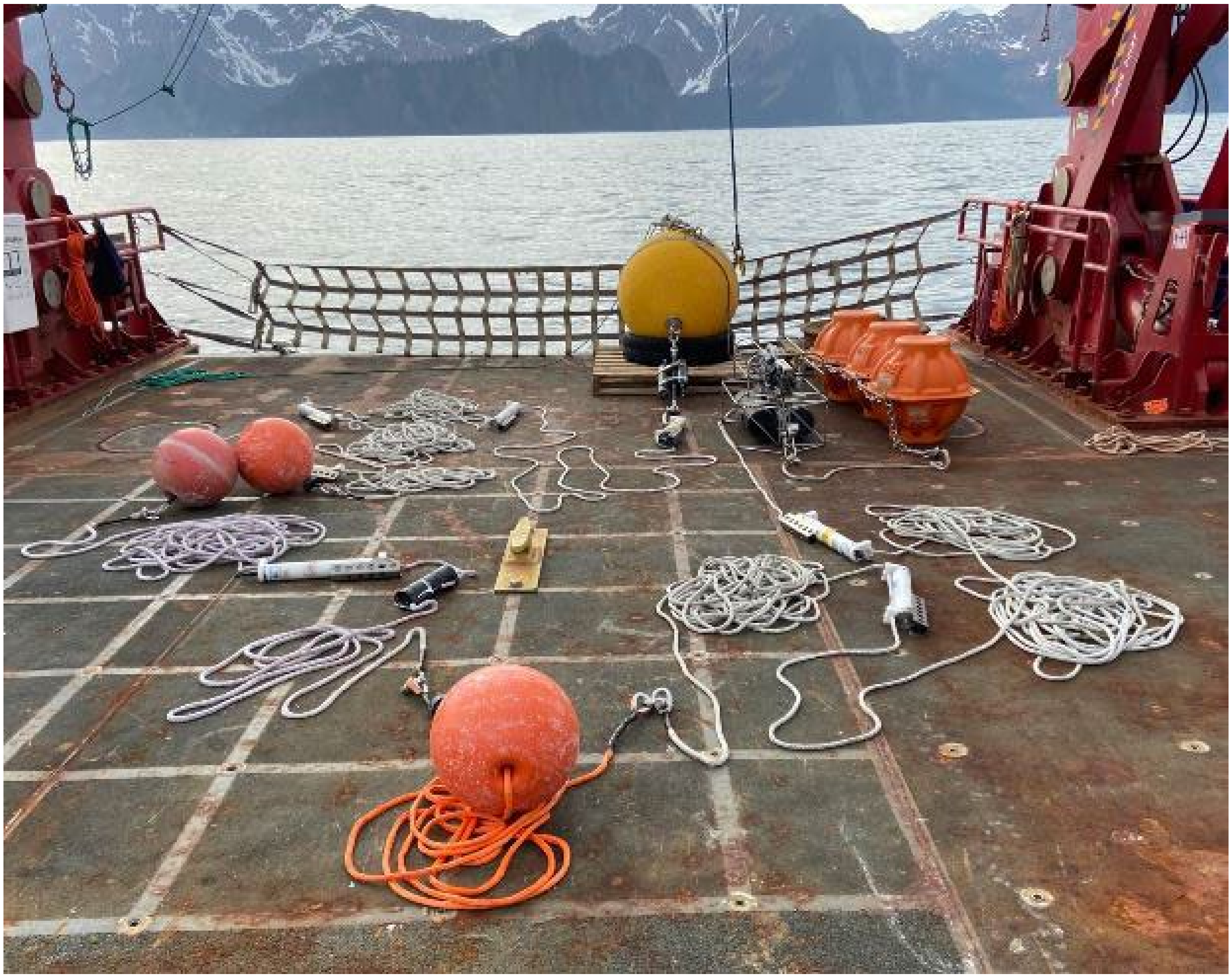

Figure 5. The GAK-1 mooring assembled on the deck of R/V Sikuliaq prior to deployment in May 2020.

RESULTS

The most complete GAK-1 monthly time series is a combined dataset that aggregates both moored CTD datalogger and profiling CTD sensor data into a single, best estimate of monthly thermal and haline conditions. Hydrographic profile sampling began in December 1970, and a mooring with at least six CTD dataloggers has been deployed at GAK-1 nearly continuously since December 1999.

Survey of GAK-1 Observations

The combined monthly profile and mooring time series through 2000-2021 (shown through most of the mooring deployment interval in Fig. 6) reveals the magnitude of seasonal fluctuations and the known out-of-phase relation between the surface and seafloor measurements that exist within the annual cycles of both temperature and salinity. Key aspects of this out-of-phase relation include the propensity for the annual minimum temperature to be recorded in March at both the surface and 100 m depth, while the maximum salinity at the surface is in March but in August at 100 m depth and in October at 250 m depth (Fig. 7). In contrast, the warmest temperature generally occurs in August at the surface, in November at 100 m depth, and in December at the seafloor. The freshest month at the surface coincides with the warmest temperature, August, while the lowest salinity at 100 m and 250 m depth is in January and February, respectively.

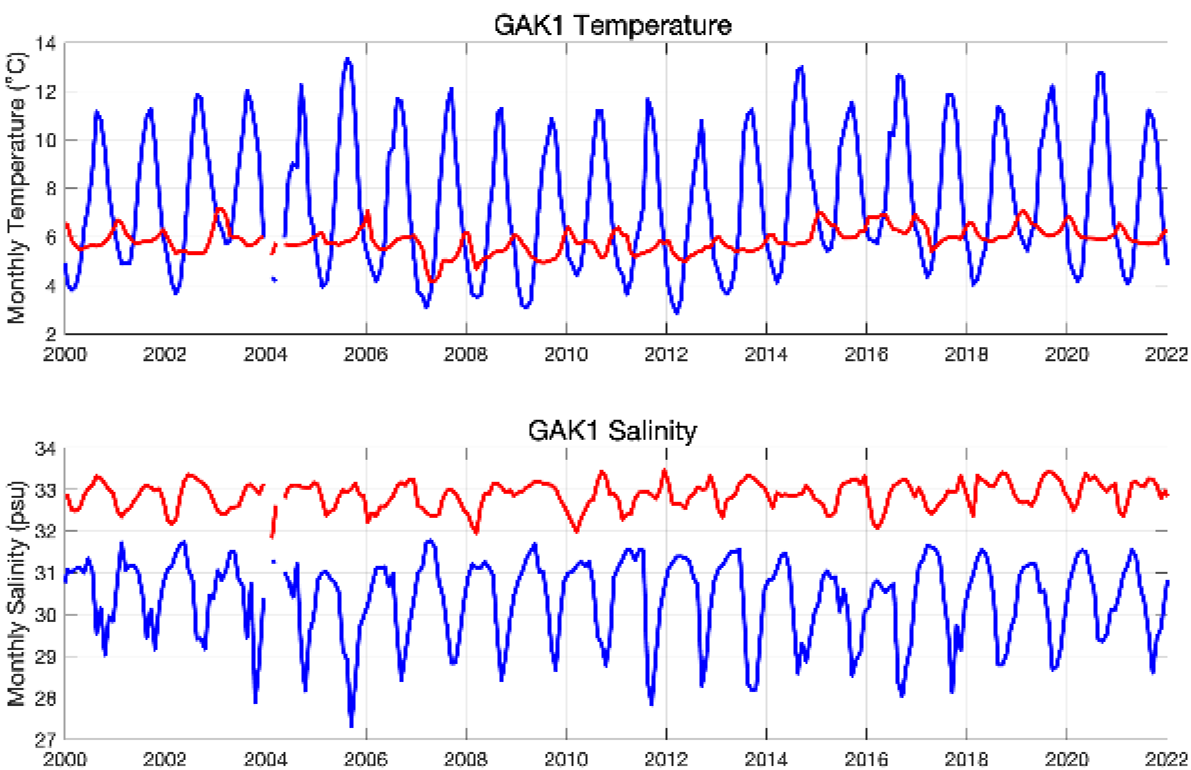

Figure 6. Monthly GAK-1 data spanning 2000-2021, most of the mooring deployment interval, from the 0-50 m average near-surface (blue) and 200-250 m average near-seafloor (red) temperature (left) and salinity (right).

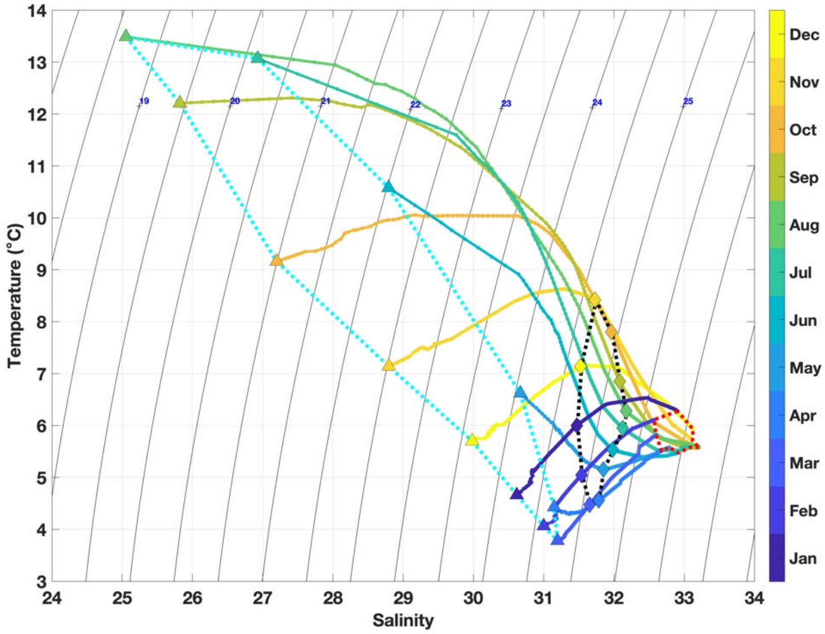

Figure 7. Mean monthly relationship between temperature (vertical axis) and salinity (horizontal axis). Dotted colored lines connect the months (denoted by colorbar at right) at the surface (cyan, triangles), 100 m depth (black, diamonds) and 250 m depth (red, no symbol). Arrows depict the direction of seasonal progression at each of the three selected depths.

Inspection of the record anomalies (Fig. 8) reveals multi-year periods of primarily warm or primarily cool anomalies. Previously identified trends (e.g., Royer and Grosch 2006, Kelly 2015, Danielson et al. 2022) show that the entire water column has a statistically significant record-length warming ($p < 0.01$, $\alpha = 0.05$) that is greater at the surface (0.22 °C decade^{-1}) than near the seafloor (0.16 °C decade^{-1}). Trends in salinity show record-length decline at the surface (-0.056 decade^{-1}) but increase near the seafloor (0.037 decade^{-1}). Analysis of the seasonality of the monthly anomalies and their trends reveals that they do not manifest equally year-round (Fig. 9), with larger salinity anomalies prevalent in late summer and fall months and thermal anomalies largest in winter and spring.

Surface-enhanced synoptic-scale fluctuations in late summer and fall months (e.g., Fig. 10) are common in the mooring records and are most prominent in the upper 30 m of the water column. These features are likely related to atmospheric forcing and internal motions (e.g., shelf waves) that may be propagating around the rim of the GOA. Other signals are clearly enhanced at interior depths or near the seafloor, such as late summer step increases in salinity in August 2021 or the fluctuations at 150-250 m depth between January and March 2022 (Fig. 10). Although amplitudes of subsurface variations are smaller than the surface-driven features, they likely reflect meaningful changes in near-seafloor nutrient concentrations (Childers et al. 2005).

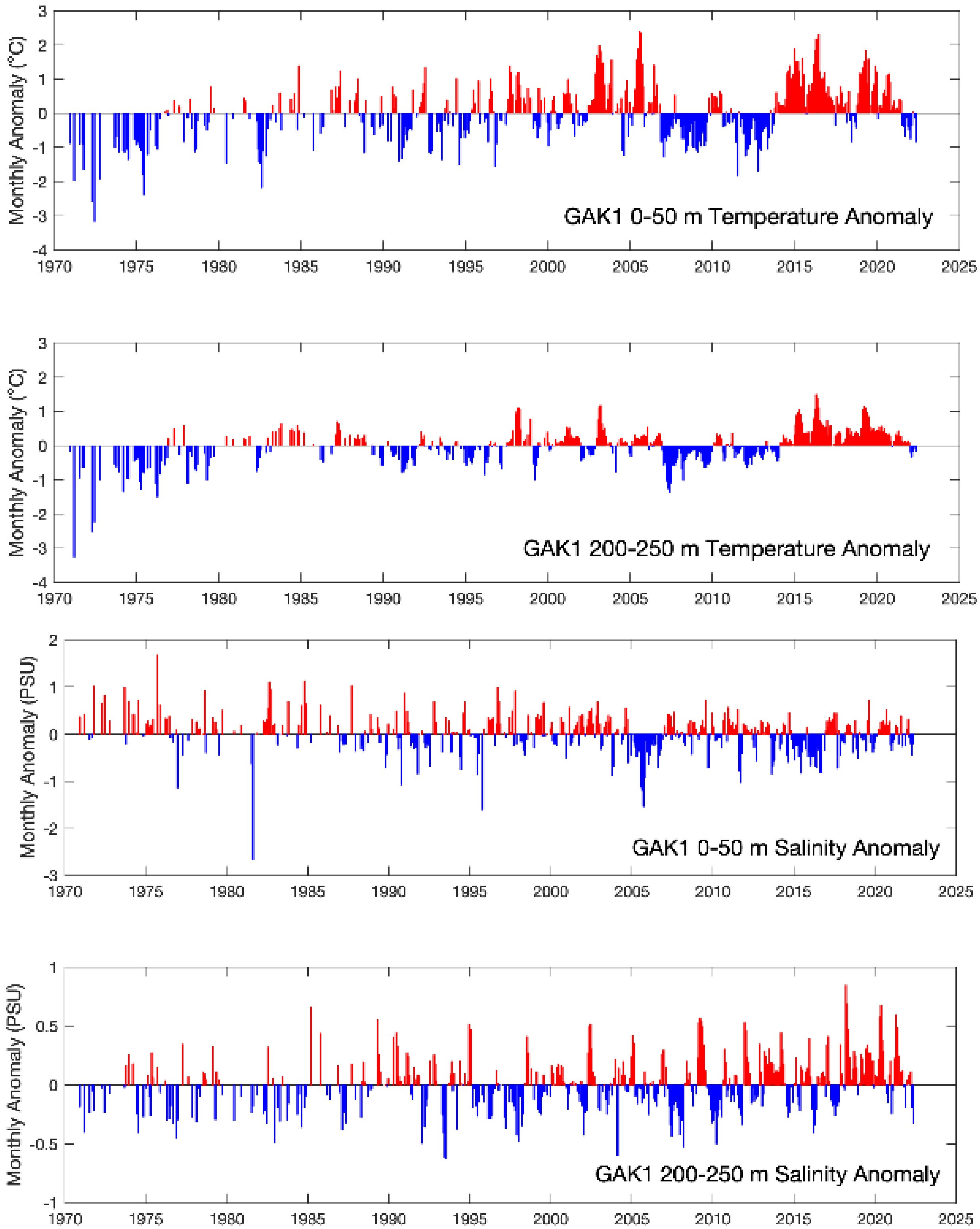

Figure 8. GAK-1 monthly anomalies of near surface (0-50 m) and near bottom (200-250 m) temperature and salinity over 1970-2022. Note change of scale amplitude for the two salinity plots.

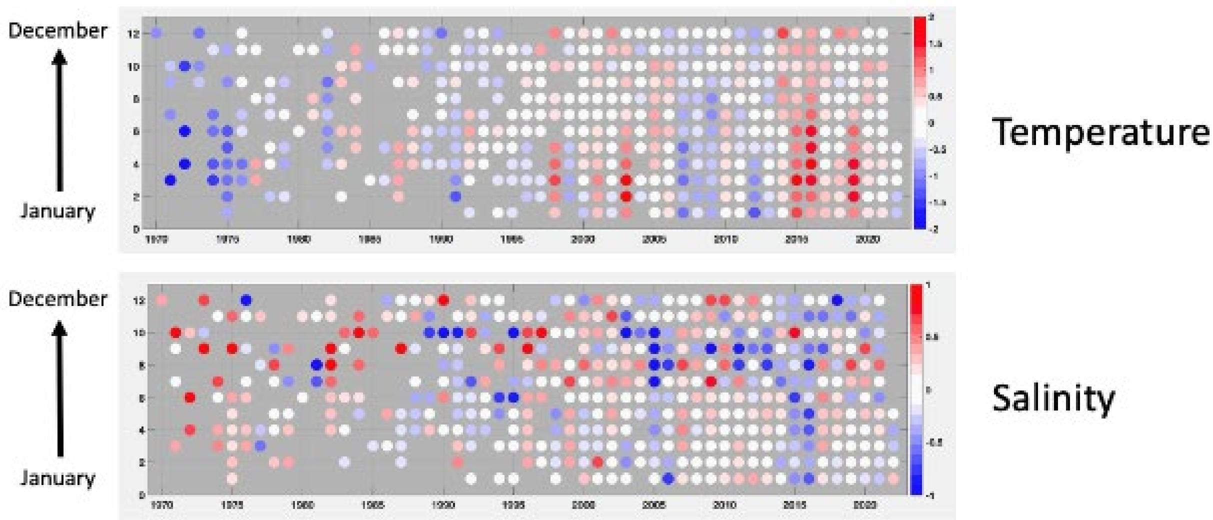

Figure 9. Anomaly grid that depicts the seasonal nature of GAK-1 temperature (top) and salinity (bottom) anomalies.

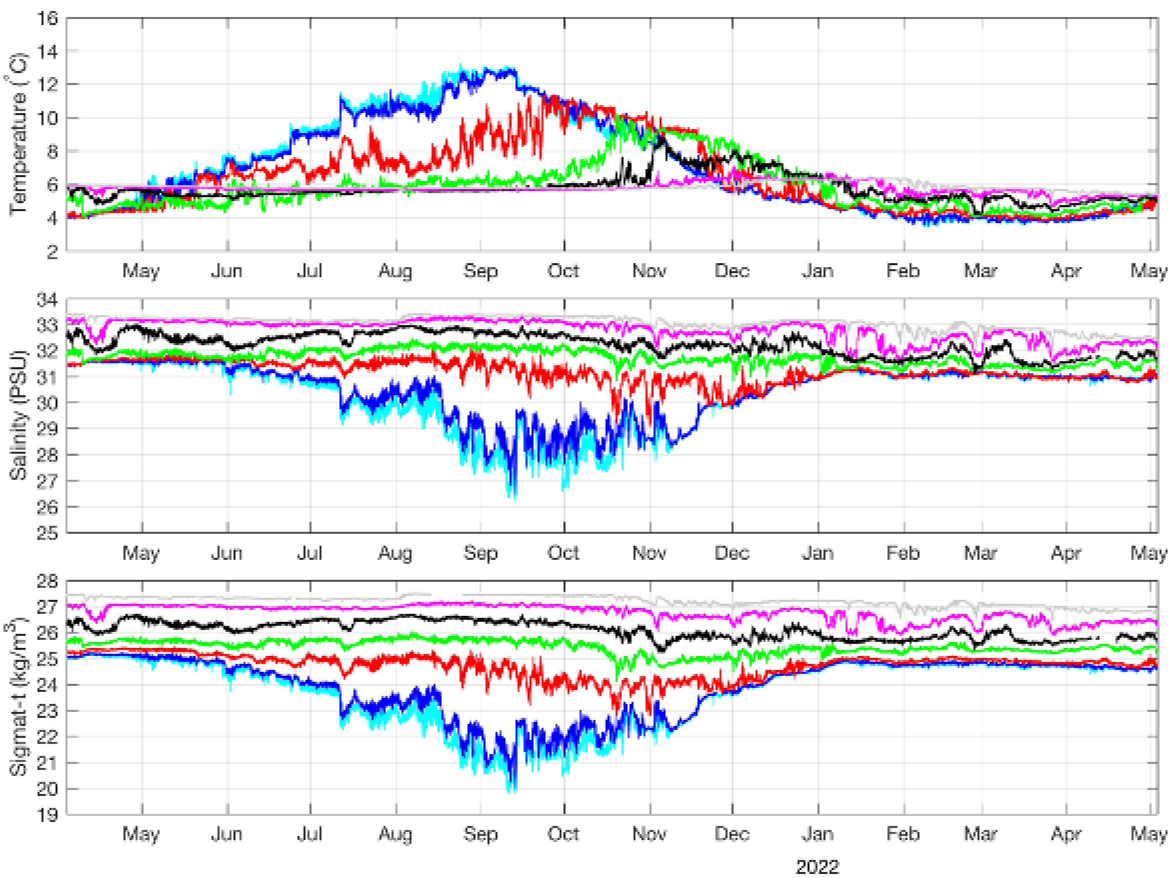

Figure 10. Temperature (top), salinity (middle) and density (bottom) from the 2021-2022 GAK-1 mooring deployment. Nominal instrument depths are denoted by color: 20 m (cyan); 30 m (blue); 60 m (red); 100 m (green); 150 m (black); 200 m (magenta) and 250 m (grey).

GAK-1 as a Reference Station

Analysis of satellite-measured sea surface temperatures from across the GOA shows that the GAK-1 location is well representative of a dominant portion of the greater northern GOA shelf, confirming our sample strategy and its location as a valuable reference point for greater Gulf of Alaska oceanographic conditions. For example, regional cross-correlations of surface thermal anomalies (Fig. 11) show that the GAK-1 reference location is more strongly correlated to the GOA northern shelf than reference sites in lower Cook Inlet, Prince William Sound, or upstream in SE Alaska.

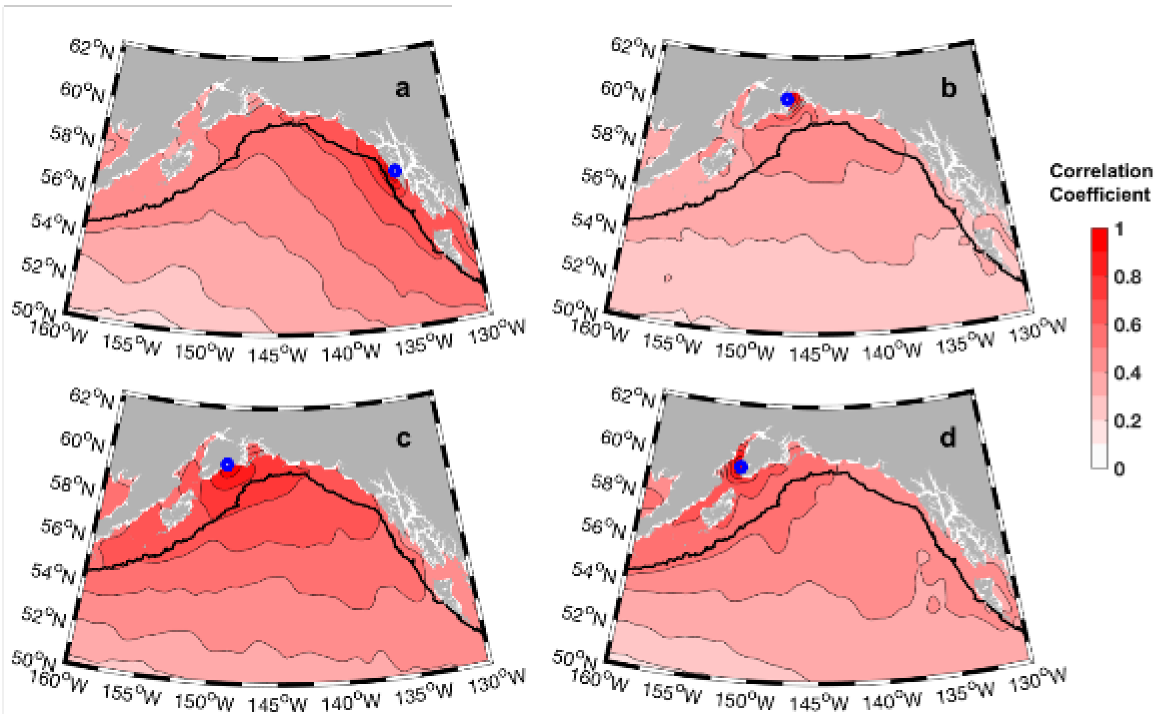

Figure 11. Cross-correlation of satellite-derived temperature anomalies relative to reference points (blue circles) at Sitka (a), western Prince William Sound (b), GAK-1 (c) and System Wide Monitoring Program (d). The continental slope is denoted with a thick black contour at the 1000 m depth level. Figure reproduced from Danielson et al. (2022).

Measurements at GAK-1 and from the across the Seward Line show that near-surface thermal variability is strongly correlated and in-phase both for the annual climatology and for monthly anomalies (Fig. 12). On the other hand, surface measurements of temperature only modestly reflect subsurface thermal anomalies over the shelf, with correlation values peaking at below r = 0.5 (Fig. 12), meaning that less than 25% of the water column thermal variance is well explained by surface measurements made at GAK-1. Subsurface shelf waters are not measured by satellites or the global Argo profiling float array. For a typical GOA shelf depth of about 250 m and surface mixed layer depth of approximately 20 m, over 90% of the shelf volume is not well monitored by satellites or floats. Thus, GAK-1 measurements provide a key environmental index of subsurface habitat conditions over the northern GOA continental shelf. We find that GAK-1 sea surface temperature anomalies are inversely correlated with near-bottom temperatures at the shelf break. This relationship is partially driven by the differential annual cycle of warming and cooling between the seafloor and the surface, but because the signal remains when the climatology is removed, there are also hints of a mechanistic link that goes beyond the annual cycle.

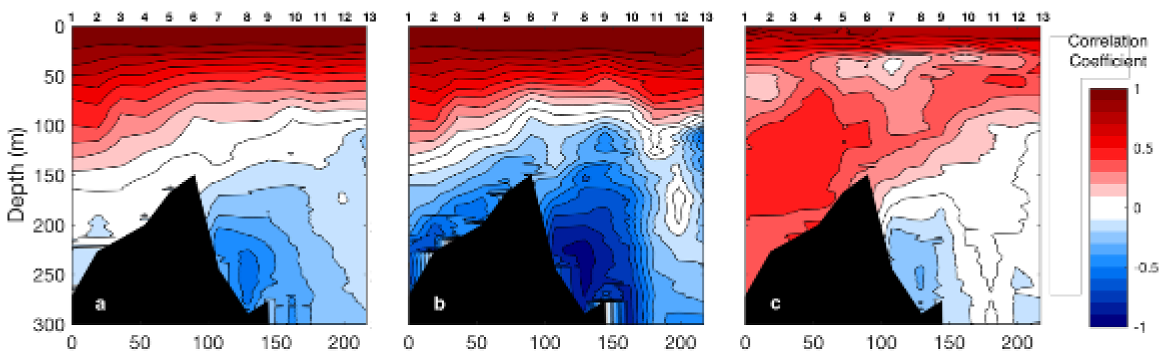

Figure 12. Correlation of temperature across the Seward Line transect (station numbers locate GAK-1 to GAK-13 at the top of each panel) relative to the surface temperature at station GAK-1. Panel (a) shows correlations that characterize the observed temperatures. Panel (b) depicts the correlation of the monthly climatology. Panel (c) shows correlations of the monthly anomalies (monthly climatology removed). Black regions depict the shelf seafloor. Correlations are computed here for 103 Seward Line occupations between 1974 and 2021. Figure reproduced from Danielson et al. (2022).

Using 50 years of GAK-1 water column data, nearly 200 years of air temperature records from Sitka, Alaska, and approximately 170 years of Gulf-wide surface temperatures from the Extended Reconstructed Sea Surface Temperature dataset (ERSST, version 5), Danielson et al. (2022) demonstrated the strength of cross-correlations between these records on an annual basis (Fig. 13). A lagged correlation analysis further revealed that the Sitka air temperature annual anomaly is a significant predictor of the water-column average temperature at GAK-1 (Fig. 14). Although mechanistic linkages between these synchronized fluctuations are not fully clear, it is possible that the Sitka air temperature's close connectivity to the marine environment and its upstream location to GAK-1 via the ACC advective corridor together drive the relation.

Other analyses undertaken in Danielson et al. (2022) speak to practical limitations of various measures of thermal conditions. For example, large-scale modes of climate variability were found to explain only a modest fraction of coastal GOA thermal anomalies. In part, this is due to limited fidelity of the available surface temperature estimates; satellite measures of sea surface temperature fail to capture 30-40% of the daily anomaly at GAK1. The representativeness of satellite-based measures of sea surface temperature varies spatially, with better performance offshore and degraded performance nearshore in regions of complex bathymetry (e.g., southeast Alaska archipelago, Prince William Sound).

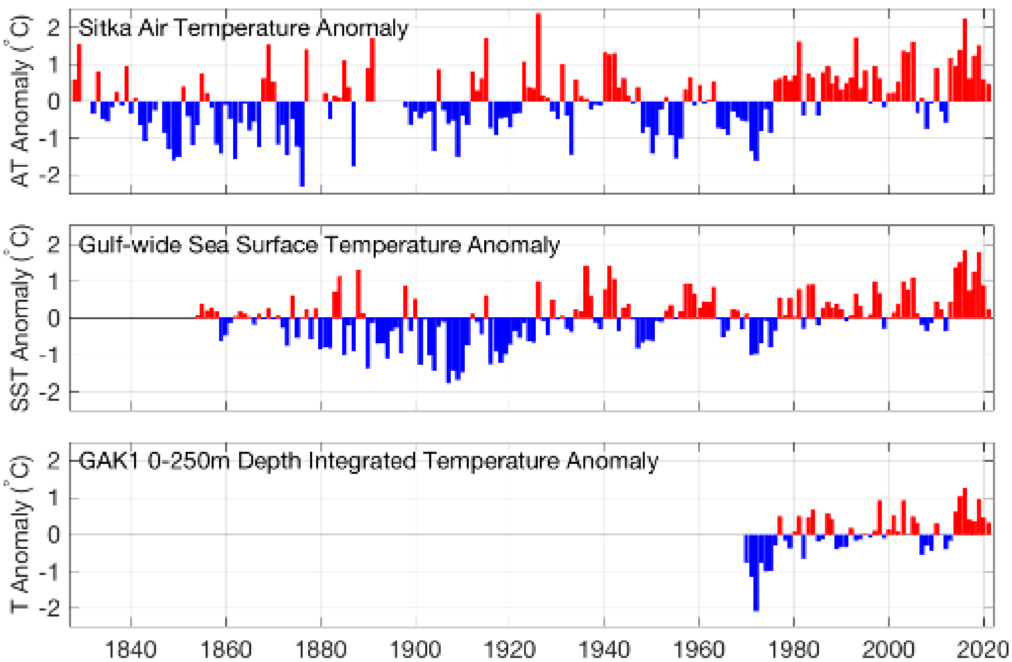

Figure 13. Annual averages of monthly temperature anomalies (seasonal climatology removed) for three long-term datasets. Upper panel: 1828-2021 Sitka, Alaska air temperature. Middle panel: 1854-2021 ERSST V5 sea surface temperature averaged over 156° W to 130° W and 56° N to 62° N. Lower panel: 1970-2021 GAK-1 water column temperature averaged across 0-250 m depths. All three records are shown relative to a 50-year baseline computed over 1970-2019. Figure reproduced from Danielson et al. (2022).

Time series analysis shows that co-variability of sea surface temperature depends on time scale of interest and on separation distance between stations. Hence, the value of GAK-1 as a proxy for other sites depends on the time scale of interest and distance from GAK-1 to the site. Sea surface temperature is not a strong predictor for near-bottom temperatures at four selected long-term monitoring CTD sites in the coastal GOA (Kachemak Bay KB6, GAK-1, Prince William Sound KIP2 and Glacier Bay GLBA20 – see Figure 15). This result speaks to the decoupling of surface and sub-surface waters through stratification and the different processes that mediate thermal conditions in each region.

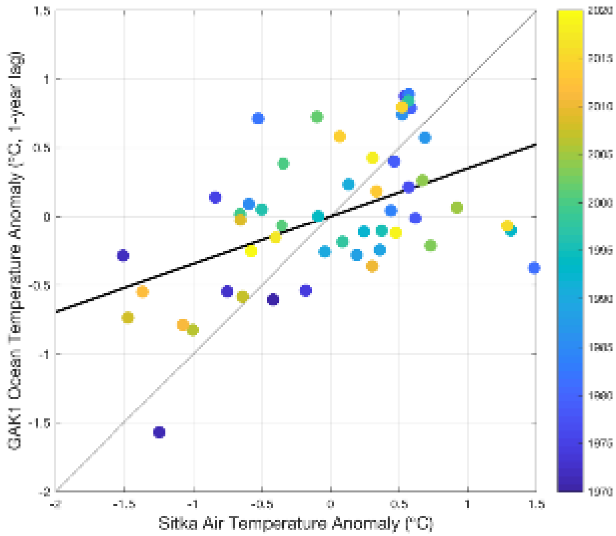

Figure 14. Relationship between the detrended annual Sitka air temperature anomaly and the following-year whole water column ocean temperature anomaly measured at station GAK-1. Thin black line shows a 1:1 slope; the thick black line is the least squares best fit line between the two records. Figure reproduced from Danielson et al. (2022).

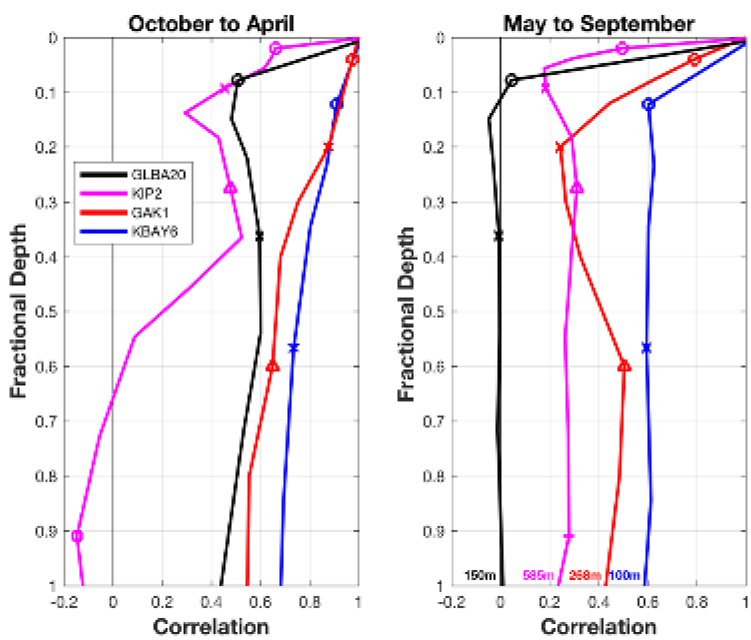

Figure 15. Correlation coefficient (r) between temperature anomalies at the surface and temperature anomalies at standard depths (0, 10, 20, 30, 50, 75, 100, 150, 200, 250, 300, 400, 500, and 550 m) for winter (left) and summer (right) season as resolved by CTDs taken at stations GLBA20 (black), KIP2 (magenta), GAK-1 (red), and the mid-transect station T09-06 in Kachemak Bay (blue). Symbols o, Δ, x and + show the location of the 10, 50, 150, and 500 m depth levels, respectively. The seafloor depth of each station is noted at the bottom of the right-hand panel.

Heat flux analyses (Danielson et al. 2022) showed that the recent Pacific marine heatwave initiated with a spatially broad anomalous air-sea heat flux in 2013. Heating continued over the northern shelf through 2014 and 2015. Near-seafloor heat in the 250 m water column at GAK-1 is primarily carried by oceanic advection rather than local heating through the surface. Hence, near-bottom warming is delayed relative to heating at the surface. During the 2014-2016 Pacific marine heatwave, far offshore waters warmed most rapidly and then cooled beginning in early 2014, while nearshore waters warmed more slowly and with close synchrony through 2014, cooled in early 2015, and then warmed again through 2016.

GAK-1 Applied to Improving Ocean Circulation Modeling

Danielson et al. (2020) describe the construction and evaluation of a northwest GOA (NWGOA) 3-D high resolution ice and ocean circulation model. The ocean component of the NWGOA model uses a wetting-and-drying algorithm to accurately reproduce the large Cook Inlet tides, and it uses the high-resolution terrestrial runoff estimates of Beamer et al. (2016) to provide a coastal boundary forcing function of freshwater inputs. GAK-1 data are used to assess model performance (Figs. 16, 17).

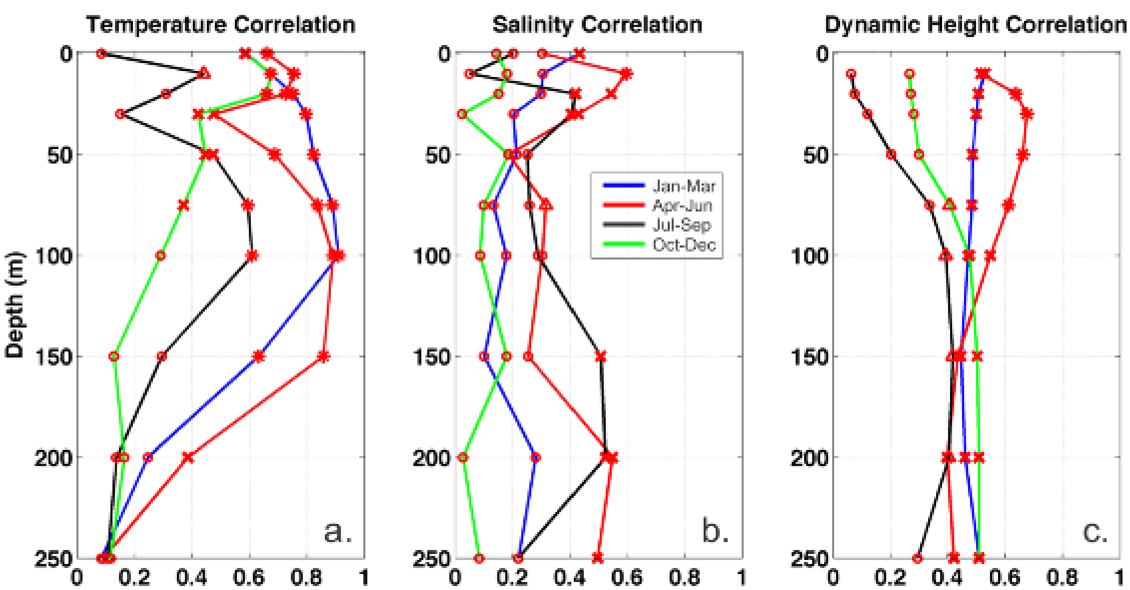

Figure 16. Correlation coefficients (r) between monthly anomalies of observations made at GAK-1 and monthly anomalies of hindcasts from the northwest Gulf of Alaska ocean model. Parameters include temperature (a), salinity (b), and dynamic height referenced to the surface (c). Line colors represent January-March (blue), April-June (red), July-September (black), and October-December (green). Symbols show correlations that are not significant (circles) and significant at the 90%, 95%, and 99% levels (triangles, crosses, and asterisks, respectively). Figure reproduced from Danielson et al. (2020).

Fig. 14 shows that the hindcast from Danielson et al. (2020) reproduces GAK-1 monthly anomalies of temperature, salinity, and dynamic height with varying levels of fidelity through the water column and through seasons. For salinity (Fig. 16b), the strongest correlations (r=0.5-0.6, $p < 0.05$) are found near the surface (10-20 m depths) and in the lower portion of the water column (below 200 m depth) in spring (April-June). This season corresponds to the rapid annual increase of coastal discharge caused by the spring snowpack melt and often includes the annual discharge peak in June (Beamer et al. 2016). In summer (July-September), the maximum near-surface salinity correlation weakens ($r \sim 0.4$, $p < 0.05$) and is located slightly deeper in the water column (20-30 m), while the correlation remains near $r = 0.5$ at 200 m depth. The model mostly does not reproduce any significant portion of the observed anomalies in fall and winter (October-March). Unsurprisingly, fall and winter are the most difficult to hindcast, as the runoff rate is low, and the signal-to-noise ratio for salinity is small.

The NWGOA model also exhibits some success in hindcasting temperature and dynamic height fluctuations. Temperature anomalies are best hindcast ($r \sim 0.9$, $p < 0.001$) in the first half of the year (January-June). Except for late in the year, when fall winds begin to de-stratify the water column, the maximum temperature correlations occur in the middle of the water column. The modeled 0-200 dbar dynamic height anomaly is significantly correlated with the observed anomaly in all seasons ($p < 0.05$ except $p < 0.1$ for spring) within a fairly narrow range of correlation coefficients of $r = 0.4$-0.5. Weingartner et al. (2005) showed that the GAK-1 0-200 dbar dynamic height is a proxy for the ACC June-August baroclinic ($r = 0.93$, $p < 0.05$), freshwater transports ($r = 0.79$, $p < 0.05$), and the ACC November-May freshwater transport ($r = 0.62$, $p < 0.05$) and freshwater content ($r = 0.85$, $p < 0.05$). The numerical model's ability to provide statistically significant predictions of the dynamic height monthly anomalies is a necessary step in being able to eventually link atmospheric and terrestrial processes that drive discharge fluctuations with their downstream consequences for the marine system.

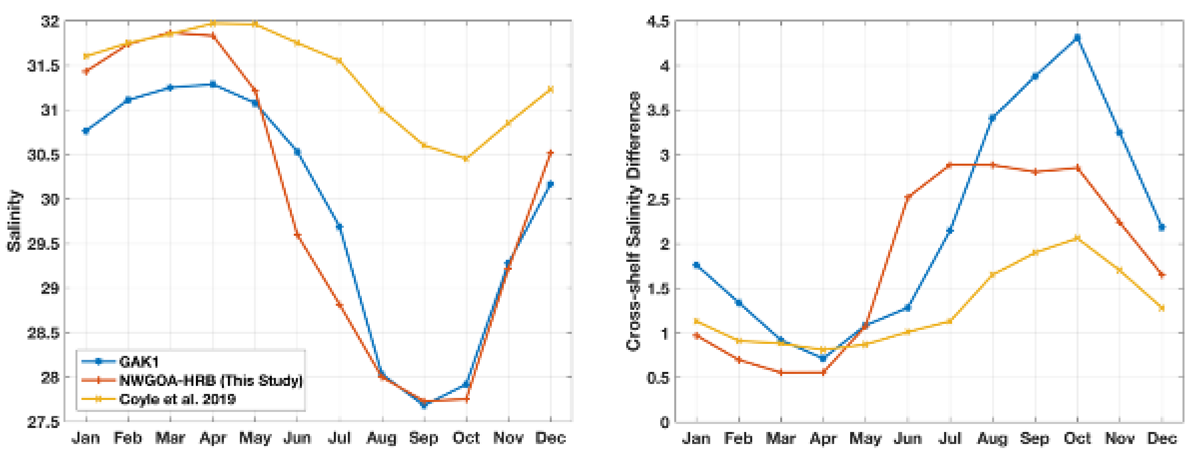

Figure 17. Comparison of the GAK-1 near surface (0-20m) observed climatology (blue) with the northwest Gulf of Alaska (NWGOA; red) numerical model described by Danielson et al. (2020) and another recent numerical model (Coyle et al. 2019; yellow).

DISCUSSION

Now at more than a half-century in length, the GAK-1 dataset is regularly demonstrating itself as a key climate record of marine conditions in Alaskan waters. Across all Alaskan Arctic and Sub-Arctic continental shelves - from southeast Alaska's Inside Passage to the Beaufort Sea - there exists no other monthly hydrographic profile time series with similar duration and consistency. The dataset documents the magnitude of environmental changes experienced by the Gulf of Alaska water column: multi-decade warming trends and alternating multi-year intervals of cool and warm conditions, including marine heatwaves, regime shifts, freshening near the surface, salinization at depth. These changes all represent meaningful changes to oceanic habitat, whose effects propagate into the marine ecosystem and through either direct bottom-up or indirect top-down controls of key species (e.g., Anderson and Piatt 1999, Arimitsu et al. 2021, Suryan et al. 2021, Weitzman et al. 2021).

The annual cycles of temperature and salinity from GAK-1 provide insights into the temporal progression of the bottom-up controls on the Gulf of Alaska coastal ecosystem, such as the timing of nutrient renewal in surface waters. Given that salinity is positively correlated with all major macronutrients (Childers et al. 2005) in subsurface waters and surface waters prior to the spring bloom, the system exhibits maximum nitrate concentrations within the euphotic zone in late winter, just prior to the onset of the spring bloom and when sufficient light and increasing stratification will allow the bloom to progress. Our finding that near-seafloor temperatures are inversely correlated with surface temperatures at GAK-1 suggests that the magnitude of on-shelf renewal of deep shelf waters is tied to the surface conditions that partially regulate thermal conditions in coastal waters. Given the known temperature-salinity relation found at these depths near the shelf break, we can thus expect that on-shelf nutrient fluxes are similarly enhanced during periods of cooler surface waters in the coastal region.

As we gain more sophistication in our understanding of environmental-ecological linkages, we also improve our ability to generate useful projections of ecosystem status and functioning. The lagged Sitka:GAK-1 relationship, although not appreciably stronger than the zero-lag correlation, provides some utility as a forward-looking environmental index (Danielson et al. 2022). Such a relationship can help inform projections of system state for factors that are strongly dependent upon water column temperatures. Thermal conditions are known to contribute statistical power to many regression-based population status estimates.

The incorporation of a coastal wall mass flux boundary condition in the NWGOA model is a different but also significant step forward for GOA circulation modeling and forecasting. Improvements occur because the proper amount of freshwater can be added to the model domain at the correct place, and the model's physics are then able to dictate the mixing, transport, and diffusion of fresh water away from the coast. These improvements are clearly seen in comparisons to GAK-1 data and to a similar ocean circulation model (Coyle et al. 2019) that uses the "old" method of distributing freshwater in the form of a spatially prescribed virtual precipitation (Fig. 17). Such improvements are important if we are to rely on numerical models to accurately predict ecological responses to environmental variability.

With 25 peer-reviewed publications and 16 reports using GAK-1 data generated over the 2017-2022 focal time interval of this report, most of which are not authored by the GAK-1 program scientific leads, it is clear that the community of Alaskan marine scientists relies on the GAK-1 dataset as a proxy baseline for marine thermal and haline conditions. Having now passed the 50-year data length milestone, the new findings presented in this report suggest the need for an updated record-length retrospective analysis of both the temperature and salinity fields together.

Although the GAK-1 study is not formally driven by scientific hypotheses, the objectives of maintaining high-quality regular oceanographic observations continue to be well served with the existing field program. As technology evolves, it may be possible to eventually collect an even more complete set of measurements at this site, but more than two decades of successful mooring deployments and recoveries using the same instrument types shows that our approach is both reliable and sustainable.

CONCLUSIONS

GAK-1 is a key half-century reference dataset for assessing environmental conditions and change in the GOA, and its value continues to increase steadily with time and through an ever-expanding set of peer-review publications, student theses and dissertations, and agency reports that utilize the record. Some aspects of the observed changes still need mechanistic explanations, such as the causes of the near-bottom salinization trend. The GAK-1 dataset documents the Gulf of Alaska manifestation of marine heatwaves, El Niño events, intervals of cool conditions, the consequences of melting glacier ice, and many other processes. Continued monitoring at station GAK-1 needs to remain a high priority through the coming decades.

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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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Brydie, A., and S. L. **Danielson**. 2020. Copper River discharges in the Northern Gulf of Alaska: freshwater distribution and evolution during the July 2019 freshet. Poster presentation. AGO-ASLO Ocean Sciences Meeting, San Diego, California, February.

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Danielson, S. 2019. Presentation to the Alaska Ocean Observing System Board, Anchorage, Alaska, December.

Danielson, S. 2019. 21st century oceanography in the last frontier. Invited Keynote Presentation, University National Oceanographic Laboratory System (UNOLS) Research Vessel Technical Enhancement Committee (RVTEC) meeting, Fairbanks, Alaska, November.

Danielson, S. 2019. Changing stratification over Alaska region continental shelves suggests altered diapycnal mixing and nutrient fluxes, Invited Talk, 3rd International Symposium "Ocean Mixing Processes: Impact on Biogeochemistry, Climate and Ecosystem", University of Tokyo, Japan, May.

Danielson, S. L. 2020. Freshwater in the Gulf of Alaska: New observations and model results. Presentation to NOAA Coastal and Marine Modeling Branch (CMMB) seminar series. Distance video presentation, December.

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Gavenus, K. A. 2022. NGA LTER near & far: Spatial & temporal scales of our education efforts. Poster presented at the LTER All Scientists Meeting 2022, Asilomar, California, September.

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Outreach

Baily, A. 2021. UAF's Seward Marine Center celebrates 50 years, UAF press release, March.

Danielson, S. L. 2020. The importance of University of Alaska-based monitoring of our oceans. Anchorage Daily News Op-Ed, 12 Dec. 2020. (This was also a UAF press release and was re-printed in January 2021 by deltawindonline.com.)

Danielson, S. 2019, Assessing recent changes in Alaska region oceanic heat content, Osher Lifelong Learning Institute, Fairbanks, AK, October.

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Appendix A: Selected Outreach Articles

Danielson, S.L. 2020. The importance of University of Alaska-based monitoring of our oceans. Anchorage Daily News Op-Ed, 12 Dec. 2020.

Data is the lifeblood of science. It provides scientists with a way to prove, refine, or disprove our ideas about how the world works. Data from the University of Alaska Fairbanks (UAF) is providing valuable information for oil spill response, public safety, and economic development efforts in the 49th state.

UAF passed a remarkable milestone this month when scientists from the College of Fisheries and Ocean Sciences completed a half-century of regular observations at a Gulf of Alaska oceanographic station. Station GAK-1 is located near Seward at the mouth of Resurrection Bay, and it has the longest set of sustained measurements of surface-to-seafloor temperature and salinity in all of Alaska's coastal and offshore waters.

What does this mean for our state? GAK-1 is providing data to drive good decision-making and help us evaluate risks to Alaska's marine ecosystem and economy as the ocean becomes warmer and more acidic due to climate change. This monitoring contributes to our understanding of melting glacier runoff in the ocean, variations in Alaska's commercial fisheries, and the population status of marine mammals.

Data collected at GAK-1 and elsewhere across Alaska's oceans provide public benefit by contributing to responsible development of marine resources, vessel operations, tourism, and public safety. Observations made from ships, autonomous underwater gliders, and oceanographic moorings all support sustainable fisheries management practices and direct responses to warming-induced blooms of paralytic shellfish poisoning.

In the Arctic, land-based ocean current mapping systems staged in Bering Strait and near Utqiaġvik are assisting marine navigation and helping the US Coast Guard with oil spill response and search and rescue missions. Moored ecosystem observatories that track everything from ocean physics and chemistry to fishes and whales are our eyes on the offshore Arctic waters through the months when ice excludes vessel traffic.

The first GAK-1 observation was taken in December 1970 by UAF faculty member Tom Royer, who then began visiting the site every month or two. Royer later used the data to help accurately predict the time it would take oil from the 1989 *Exxon Valdez* oil spill to reach Kodiak.

We recognize that compared to thousands of years of Indigenous observations, 50 years is a blink of an eye. While useful, long-term systematic scientific data collections are just one cornerstone of a comprehensive resource management framework. Scientific knowledge and Indigenous knowledge accumulated through Alaska Native oral traditions both provide critically important references for assessing change. Both are necessary for responsible and equitable management of Alaska's marine resources, and the University of Alaska is an ideal place for bridging the two systems of knowledge.

Although monitoring can be expensive, the alternative—not establishing and maintaining key data records—can be even more costly, far beyond dollars and cents, to ecological, cultural, and social impacts that affect the well-being of us all.

Every dollar the state of Alaska spends on research at the University of Alaska brings in about six more. Diminished funding to our university system threatens our research capacity, and, in turn, jobs, public safety, and our economy. Our shared goals of healthy ecosystems and subsistence harvests, responsible development, and public safety depend in part on a strong University of Alaska.

Baily, A. 2021. UAF's Seward Marine Center celebrates 50 years, UAF press release, 2 Mar. 2021

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UAF's Seward Marine Center celebrates a half-century

March 2, 2021

Alice Bailey
907-328-8383

On Dec. 11, 2020, the shiny, silver research vessel *Nanuq* departed Seward carrying a small group of faculty and staff from the University of Alaska Fairbanks.

Onboard was a cylindrical array of sampling containers and instruments that looked a bit more frilly than usual. It was adorned with colorful balloons, including a large "happy birthday" helium balloon, and a bottle of sparkling fruit juice nestled within the cluster of equipment.

Capt. Brian Mullaly stopped *Nanuq* at an unmarked spot known as Gulf of Alaska Station 1, or GAK-1, in Resurrection Bay. Researchers have been returning there for 50 years, using vessels primarily homeported at the Seward Marine Center. Their measurements form the longest sustained set of temperature and salinity data in Alaska's coastal and offshore waters.

Photo by Gillian Braver. UAF faculty members Seth Danielson, left, and Russ Hopcroft join Seward Marine Center staff to celebrate the 50th anniversary of the GAK-1 oceanographic station aboard Nanuq in December 2020.

After arriving, the group popped the cork on the sparkling cider, untied the balloons and got to work lowering equipment over the side of *Nanuq* to maintain the time series.

The Seward Marine Center likewise celebrated its 50th anniversary in 2020. GAK-1 data and numerous other programs supported by SMC over the past half-century have proved critical for understanding how Alaska's marine ecosystem functions.

"For the last 50 years, we have provided consistent maritime access to the Gulf of Alaska and the Arctic," said Doug Baird, SMC's director and marine superintendent.

Part of the UAF College of Fisheries and Ocean Sciences, SMC's campus is located on the Seward waterfront near the Alaska SeaLife Center. The centers collaborate on research, funding, and student support and mentoring.

Two state-of-the-art research vessels operated by the university are homeported in Seward's harbor: *Sikuliaq*, a 261-foot global class, ice-capable ship owned by the National Science Foundation, and UAF's 40-foot coastal research vessel, *Nanuq*.

Seward is a town of about 2,700 people, and SMC's influence has been substantial. The center is one of Seward's largest year-round employers. Full-time staff operate research vessels, assist with scientific equipment, maintain facilities and provide other support to scientists who base their fisheries, marine biology and oceanographic research out of Seward.

SMC tries to hire locally, and many crew members have taken courses at Seward's Alaska Vocational and Technical Center. "The SMC campus is one of the anchors that keeps Seward viable through the winter," said Terry Federer, director of the Maritime Training Center there.

The K.M. Rae Marine Education Building is an important venue for various community events, such as concerts, election polls, and a popular high school science competition known as the Tsunami Bowl. These activities have depended on generous volunteer support by local people and businesses.

Photo by Britton Anderson. Sikuliaq docks at the Seward Marine Center's pier.

SMC also attracts science teams from around the world, funded by regional, state, federal and international agencies. Their spending bolsters grocery stores, machine shops, shipping companies and other local businesses.

On Dec. 14, 2020, Seward Mayor Christy Terry presented a proclamation commemorating SMC's 50th anniversary. "SMC is such a benefit to Seward, I just can't stress that enough," she said. "The level of academics and skilled technicians connected to SMC raises the caliber of Seward, adds to our population, and allows us to tap into some of that research."

The beginning

The Alaska State Legislature created the Institute of Marine Science in 1960. It was one of three major research institutions at the University of Alaska at the time. IMS originally had an oceanographic station in Douglas, across Gastineau Channel from Juneau. The station was relocated to the deepwater port of Seward in 1970.

Seward was seen as a better base for research cruises because its road connection allows more reliable, affordable transportation of people and supplies. Scientists had better luck obtaining funding for Bering Sea research with a shorter transit out of Seward instead of Southeast Alaska. The town's location at the head of Resurrection Bay also is perfect for research in the northern Gulf of Alaska.

Researchers wanted to use the seawater in Resurrection Bay for laboratory studies because it could be pumped from deep water, where it was not affected by surface conditions. People also thought that a less isolated location would encourage faculty and staff to stay long-term.

The move met with political resistance because some lawmakers wanted IMS to stay near Juneau. But eventually it was approved, and IMS faculty, staff and students made it happen.

The research vessel *Acona*, used by IMS in Douglas, transported crew members and the ship's equipment to its new home port in Seward. A National Guard cargo plane carried most of the laboratory equipment. Dolly Dieter, an IMS technician at the time, recalled taking the ferry and then driving the remaining lab equipment in a beat-up van.

"It had a hole in the middle of the floor probably 2 feet wide, and I just laid a blanket over it," she said. "It was December, and I got to Tok and it was minus 50. And then the water pump went out and I was stopping at every stream that wasn't frozen, getting water to put in the radiator. But those were the things you did. Just keep this thing going."

Dieter eventually became SMC's marine superintendent, then director. She was also instrumental in working with NSF on plans for an Arctic ship that would be built after her tenure there.

Photo courtesy of the Seward Marine Center. Acona, the first research ship homeported at SMC, pauses near a glacier. Acona was moved to Seward from Douglas, Alaska, in 1970.

The new location was called the Seward Marine Station, Seward Marine Center or just IMS. In 1987, SMC became part of the UAF School of Fisheries and Ocean Sciences (now CFOS). Today, IMS is housed within CFOS and serves as its central research organization.

The Seward campus facilities were meager to begin with. The Alaska Railroad's old repair shop was used as the warehouse. Part of the building was rented out to AVTEC to raise money for the first laboratory space, which is still known as the "yellow building."

Leonard Weimer became SMC's first port engineer, after moving there from the IMS station in Douglas. He converted the warehouse boiler room into a machine shop that could support the *Acona* and was instrumental in keeping the ship and campus facilities running smoothly.

SMC hired Seward residents to support the ship, which established a connection between the center and the community. The center's finances were spread thin in the early years, but the hard-working faculty and staff have always been dedicated to keeping science operations going.

The laboratory

To replace the first lab, a more extensive laboratory was completed in 1978. In 1982, it was named the D.W. Hood Laboratory after IMS's second director, Don Hood. The same year, the education building was finished and named after K.M. (Peter) Rae, the founder and first director of the UAF Institute of Marine Science.

CFOS faculty emeritus AJ Paul and his wife, Judy McDonald Paul, came to Seward in 1975 to help design the seawater system for the lab. They stayed at SMC for 27 years.

Photo courtesy of the Seward Marine Center. Judy McDonald Paul shows the egg clutch of a red king crab in SMC's Hood Laboratory. Scientists used the lab's seawater system to study the reproductive biology of crabs to aid in fisheries management.

The high-quality seawater running through the lab could support a diverse range of organisms, from phytoplankton to crustaceans to halibut. Among other things, Paul and McDonald Paul used the lab to observe some of Alaska's iconic species, such as king crab, halibut, pollock and shrimp, that are harvested commercially but are difficult to study in the wild.

"Crabs are like aliens — they don't have red blood, they don't have backbones, they don't breathe air. To elucidate their life history, you pretty much have to do it in captivity. You can't do it in situ — they live out too deep and too far away from anybody," said Paul.

The lab drew researchers from around Alaska and the world who conducted a wide array of experiments there. Graduate students and technicians came from Fairbanks to get their feet wet as scientists. Students stayed from a couple months up to a couple of years developing thesis research on topics ranging from paralytic shellfish poisoning to fisheries oceanography.

A succession of research ships

SMC is a primary docking facility for academic research vessels working in Alaska.

Acona was the first IMS ship homeported at Seward. It was designed for near-coastal research, but that did not stop scientists from venturing farther out.

"Once you got out past Resurrection Bay on the *Acona* , it was rock and roll," said Paul. "We called it the 'blue canoe' because it rolled and pitched and yawed all at the same time."

In 1980, the National Science Foundation replaced *Acona* with the 133-foot Alpha Helix, which was classified as a small regional-class vessel. Scientists once again pushed the ship to the limit, often on long voyages in extreme conditions that made even the most seaworthy sailors ill.

Alpha Helix supported major studies throughout the Bering Sea, Aleutian Islands and Gulf of Alaska. In the 1990s, researchers frequently took the ship to Arctic waters, including the Chukchi and East Siberian seas. One year, *Alpha Helix* traveled a total of more than 25,000 miles, slightly farther than the Earth's circumference.

Even though *Alpha Helix* performed admirably for its size, scientists needed a ship better suited for the open ocean and capable of navigating Arctic sea ice. Scientific teams were becoming larger and more multidisciplinary, and they required more berths, laboratory space and deck space.

In 2001 Congress appropriated funding for a design study of an ice-capable ship. Alpha Helix was used for science operations through 2004 and was sold a few years later.

SMC was left without a ship for several years, so in the meantime scientists used ships based out of other locations and Little Dipper, a smaller vessel homeported at SMC that supported coastal research.

Photo by Tom Kline. Alpha Helix carries scientists and students to a sampling location in Aialik Bay, south of Seward, in 1989.

In 2009, after almost 30 years of development and consideration of vessel designs, NSF funded construction of a new ship. It was one of the first projects funded by the economic stimulus package created by Congress known as the American Recovery and Reinvestment Act.

The ship was named *Sikuliaq*, after the Inupiaq word for "young sea ice," because it can work in ice up to 3 feet thick, about half a winter's worth of Beaufort Sea ice growth.

Sikuliaq is the only ice-capable vessel in the U.S. academic research fleet. It accommodates 24 scientists, plus two marine technicians and a crew of 20.

The ship extends the research season and possibilities in the Bering, Beaufort and Chukchi seas. Ship time is eagerly sought by UAF scientists and students, as well as researchers from around the world.

"UAF and SMC went from operating a regional class research vessel to operating a global class research vessel, joining the ranks of Woods Hole Oceanographic Institution, Scripps, the University of Washington, and Lamont-Doherty Earth Observatory in the academic fleet," said Steve Hartz, who worked at SMC for 31 years.

As *Sikuliaq*'s science operations manager, Hartz put together the technical team that designed, installed and integrated science systems aboard the ship. When Hartz retired in 2020, UNOLS recognized his contributions to seagoing research.

Sikuliaq was constructed in Marinette, Wisconsin, about three miles from Hartz's childhood home. In 2014, he sailed on the ship's maiden voyage from the Great Lakes to Alaska, and helped test equipment and conduct the ship's first science operations while underway. *Sikuliaq* arrived at its homeport in Seward in 2015.

Sikuliaq is equipped with sonar, satellite communications, and computer systems capable of supporting a myriad of instruments and gear brought onboard by scientists. Cranes, oceanographic winches and overboarding frames raise and lower scientific equipment. That allows researchers to collect samples, use remotely operated vehicles, and conduct surveys throughout the water column and sea bottom.

Special design features reduce noise transmission in the water to minimize the disturbance of marine mammals, fish and subsistence hunting. Students can experience research activities from afar through the ship's virtual classroom.

"If you compare the *Acona* to the *Sikuliaq*, it's like comparing a motor scooter to a Cadillac," said AJ Paul.

Photo by Ethan Roth. Sikuliaq supports scientific research in the Beaufort Sea in October 2020. The ship can break through ice 3 feet thick.

In May 2020, *Sikuliaq* gained international attention as the first U.S. academic research vessel to resume operations after the onset of the coronavirus pandemic. On a cruise operating under strict COVID-19 safety protocols, the science team was reduced to three UAF faculty who worked around the clock and relied heavily on the ship's crew and technicians.

The cruise was completed without a single COVID-19 case. Sikuliaq's coronavirus operations plan was shared with other vessels to help them safely navigate the uncharted waters of a global pandemic.

Monitoring the Gulf of Alaska

On Dec. 10, 1970, CFOS faculty emeritus Tom Royer used Acona to collect a series of seawater samples in Resurrection Bay and the adjacent continental shelf. These measurements established the time series that began at GAK-1, which is now one of 15 monitoring stations in a 150-mile transect called the Seward Line.

Royer was primarily interested in temperature and salinity — two of the most important measurements in physical oceanography. Pinning down what was controlling the flow of water in and out of Resurrection Bay could help explain ocean circulation in the Gulf of Alaska.

Scientists and technicians have diligently maintained the data series ever since that chilly December day, even when it meant holding on for dear life in a storm. A marine superstition arose that passing research ships had to stop at GAK-1, and so they did, even after a 30-day research cruise when everyone was ready to get back to Seward.

"The value of long-term monitoring is impossible to quantify. No amount of money can return us to the past to collect observations," said CFOS oceanographer and faculty member Seth Danielson, who now leads the GAK-1 program.

The creativity of researchers was critical for maintaining the unbroken flow of data. When funding was short, scientists found a way to keep their projects going. For instance, sometimes *Acona* and *Alpha Helix* cruises ended early because of bad weather, so those paid ship days could be used to maintain long-term ecological programs and establish new studies.

The scientists' eagerness to learn about Alaska's marine ecosystems and the SMC staff's willingness to support them paid off in 1989 when the tanker Exxon Valdez leaked 11 million gallons of crude oil in Prince William Sound.

Photo courtesy of the Seward Marine Center. Marine technicians catch plankton by towing a net from Acona.

UAF scientists and technicians were among the first at the scene. According to the university's 1989-1990 annual report, *Alpha Helix*'s schedule was cleared so they could begin researching the spill. The ship even supported a small submarine so they could monitor oil in the water column and on the ocean floor.

Scientists already had an inkling of where and how fast the oil was going to spread, thanks to 20 years of measurements collected throughout the gulf that revealed how water moves along the coast.

Data from GAK-1 and other places helped Royer identify the Alaska Coastal Current. In a paper published by UAF's Geophysical Institute the same year as the oil spill, he defined the current as a "stream of low-salinity water flowing like a river within the sea."

The current flows along the coast from Southeast Alaska into the Bering Sea, and then into the Arctic Ocean. "I did a rough estimate of the amount of freshwater flowing into the gulf from the coast of Alaska and found that it exceeds the flow of the Mississippi River," Royer recalled recently.

The Alaska Coastal Current helps create Alaska's highly productive fisheries. It disperses invertebrate and vertebrate larvae and provides habitat for juvenile salmon entering the ocean from their natal streams.

And the *Exxon Valdez* oil spill occurred right in the middle of it.

Knowledge of the current helped Royer talk to communities about how to respond to the catastrophe.

"I was on a teleconference with the City Council of Kodiak a few days after the oil spill, and they were debating as to whether to send their booming material to Valdez," he said. "They wanted my opinion, and I was sorry to tell them that the oil was headed their way."

Keeping watch on the waters

Today, SMC supports a growing network of ocean observatories in California, Oregon, the Gulf of Alaska, the Bering Sea, Alaska's Arctic and Antarctica.

These observatories often rely on anchored systems called moorings, which have sensors and other instruments attached to cables and floats extending from the surface to the seafloor. Moorings can be left unsupervised for a year while they continually log data.

Where early long-term monitoring projects primarily focused on physical oceanography, moored observatories now collect information on many aspects of the ecosystem. They provide year-round context for more extensive ship-based studies, and are handy when important ocean events do not coincide with visits by research vessels.

Mooring systems can be enormous, and they have to be built somewhere onshore. This is where the SMC mooring shop comes into play.

UAF's mooring operations were first stationed in Fairbanks under the direction of Bill Kopplin, John Smithhilser and then David Leech, the mooring technicians who were responsible for designing, building, installing and maintaining these ocean observing systems.

In 1998, a basic mooring system was installed at GAK-1, an effort guided by

CFOS faculty emeritus Tom Weingartner, who had inherited managing GAK-1 from Royer. At that time, the CFOS mooring shop was moved from Fairbanks to SMC to be closer to the water.

In 2013, NSF funded an expansion of SMC's mooring shop to accommodate growing interest in year-round oceanographic monitoring, which has only accelerated since then.

"We are a pretty serious staging place for Alaska," said Peter Shipton, the current lead mooring technician. "We have twice as many instruments now as we did in 2013. Scientists are always trying to get more measurements."

Shipton loads the mooring cables with sensors and other instruments strategically placed at different depths to accommodate everybody's needs. Chemists want sensors close to the surface that measure the light and nutrients that fuel phytoplankton growth. Biologists may use sonar equipment to record the presence of fish and zooplankton, or passive acoustic equipment to record noises made by marine mammals. Benthic biologists focus on the depths of the ocean and are interested in catching sinking sediments or taking pictures of the seafloor. And physical oceanographers want well-distributed measurements throughout the entire water column.

Every year, the entire mooring system has to be pulled out of the water so the data can be retrieved and instruments cleaned. Fresh sensors are attached to the cables, and old ones are taken back to shore to be recalibrated. "Turning around" moorings, as this is called, is no small feat. It requires skilled technicians and crew to handle the large, heavy, barnacle-encrusted equipment as it swings overhead while being pulled out of the water onto the deck of a ship rocking in the high seas.

Photo by Ana Aguilar-Islas. Paul St. Onge, Seth Danielson and Ethan Roth deploy a mooring wire on which an instrument will travel up and down four times a day measuring temperature, salinity, depth, chlorophyll fluorescence, dissolved oxygen, nitrate, colored dissolved organic matter and particle backscatter. The photo was taken on Sikuliaq in the Northern Gulf of Alaska Long-Term Ecological Research area in May 2020.

Monitoring programs based out of Seward are part of a larger network of ocean ecosystem observations supported by the North Pacific Research Board, the Murdock Charitable Trust, the Alaska Ocean Observing System, NSF, the Exxon Valdez Oil Spill Trustee Council, and other organizations, institutions and agencies.

Maintaining the continuity of year-round observations is crucial as Alaska's waters are affected by climate change. For example, the recovered data shows that ocean acidification is a consequence of air pollution. Acidification threatens organisms that have calcium-based shells, like clams and mussels, and the ecosystems and fisheries that depend on them.

Inspiring young scientists

SMC has hosted a regional high school science competition, part of the National Ocean Sciences Bowl, every year since 1998.

UAF was one of the first institutions in the country to participate in the competition, which was designed by the Consortium for Oceanographic Research and Education in Washington, D.C., to help inspire high school students to learn about oceans. Now the Consortium for Ocean Leadership runs the national program.

Judy McDonald Paul was the first Alaska regional coordinator, then passed the role to SMC employee Phyllis Shoemaker when she retired. The regional competition has become quite popular in Seward and has always relied on local volunteers, UAF faculty and support from various businesses.

The first Alaska NOSB was hosted by the newly built SeaLife Center. Now the science bowl is held at SMC's Rae Building, the high school and other places in town.

Except when there's a pandemic, Seward experiences an influx of teenagers every spring as small teams arrive from all over Alaska to compete. They answer rapid-fire questions about the ocean and present their research papers. The winning team goes to the national competition, which is hosted at a different participating institution each year. Seward hosted the national competition in 2008.

In 1999, a team named Tsunami from Juneau-Douglas High School won, prompting the news release title, "Tsunami swamps rivals to win 1999 Alaska Region — National Ocean Sciences Bowl." They won again in 2000 and 2001, and by then everyone loved the catchy name. The organizers eventually named the entire competition the Tsunami Bowl.

The Tsunami Bowl has not experienced any actual tsunamis, but some years have been more challenging than others.

"One year there was an avalanche on the Seward Highway, so half the teams traveling to Seward were stuck on the other side of Moose Pass," said Shoemaker. "We did the research presentations via videoconference — and that was before it was so easy to do with Zoom. Once the avalanche was cleared, the teams all managed to get to Seward for the quiz bowl."

Looking toward the future

Even with modifications for the pandemic, it looks like SMC has a busy year ahead.

The first-ever virtual Tsunami Bowl, themed "Plunging into Our Polar Seas," will proceed in March 2021. Teams from Anchorage, Cordova, Eagle River, Gustavus, Juneau-Douglas, Ketchikan and the Mat-su Valley are participating.

Nanuq will cruise the coast, providing a platform for maintaining long-term monitoring projects and other research, and will be used for a graduate-level oceanography field techniques course. *Sikuliaq* is scheduled for cruises stretching from Oregon up to the Gulf of Alaska, the Aleutian Islands and the Beaufort Sea.

Designs are being discussed for a new pier that will better accommodate *Sikuliaq* and other ships of the same size, as are plans for a new warehouse to stage equipment for projects in Alaska and around the world.

And, as usual, SMC's personnel will be busy orchestrating logistics, building and maintaining mooring and ship-based equipment, facilitating COVID safety protocols for science teams, and performing countless other services.

"The Seward Marine Center has been a central part of our mission as a leader in marine research and education, and we look forward to the next 50 years," said CFOS Dean Bradley Moran.

APPENDIX B: SELECTED PEER-REVIEWED PUBLICATIONS

Danielson, S. L., T. D. Hennon, D. H. Monson, R. M. Suryan, R. W. Campbell, S. J. Baird, K. Holderied, and T. J. Weingartner. 2022. Temperature variations in the northern Gulf of Alaska across synoptic to century-long time scales. Deep Sea Research Part II: Topical Studies in Oceanography 203:105155.

Open access publication available at:
https://www.sciencedirect.com/science/article/pii/S0967064522001400

Danielson, S. L., D. F. Hill, K. S. Hedstrom, J. Beamer, and E. Curchitser. 2020. Demonstrating a high-resolution Gulf of Alaska ocean circulation model forced across the coastal interface by high-resolution terrestrial hydrological models. Journal of Geophysical Research: Oceans, 125(8):p.e2019JC015724.

Open access publication available at:
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019JC015724