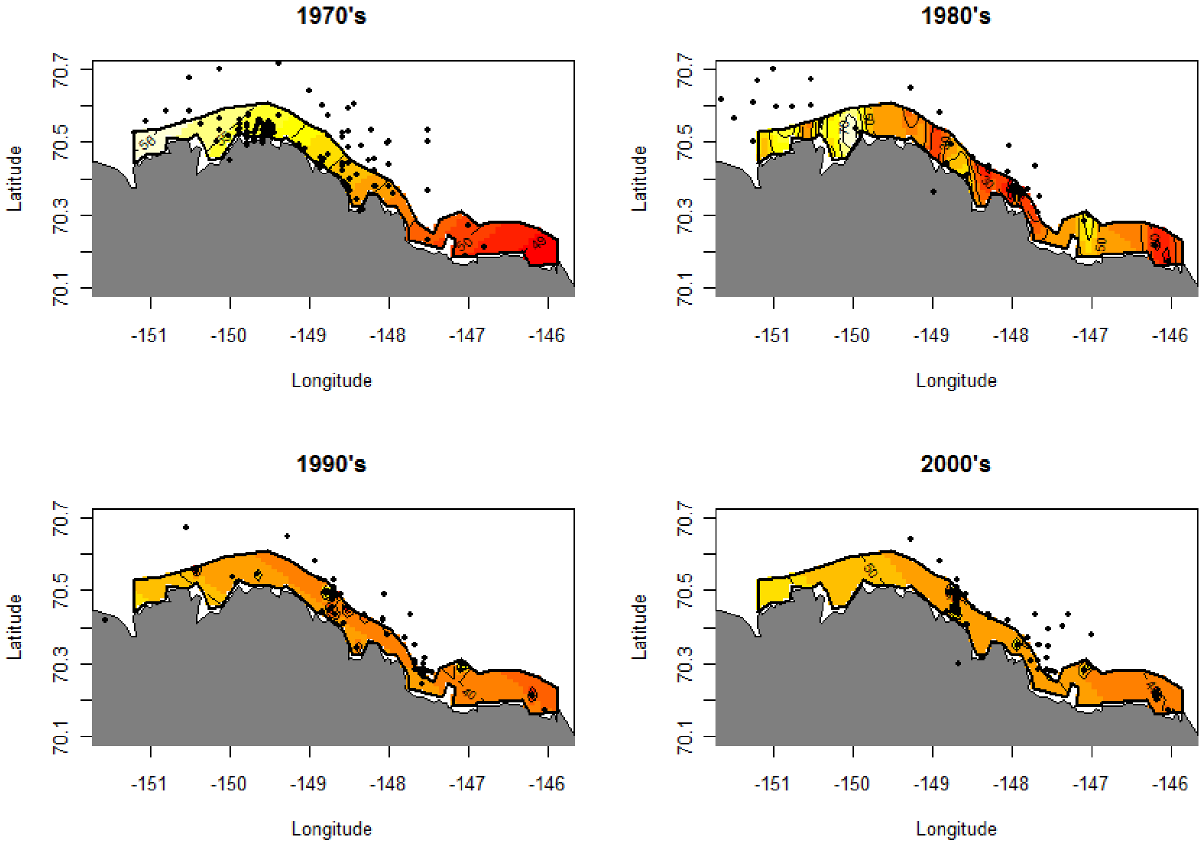
Advance Monitoring Initiative

Arctic Coastal Integrated and Comprehensive Data Mining and Assessment Project



Geostatistical prediction contours for percent mud for the western Beaufort Sea for 1970, 1980, 1990, and 2000. The solid points are the locations of sampling points within each decade. The sampling polygon used in spsurvey is the solid line.

Final Report

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INTRODUCTION

During the past 30 years Alaska's Arctic Coastal Region has experienced increased anthropogenic activities following mining and petroleum-related development, and increased urbanization of coastal communities. Integration and synthesis of observations and development of new monitoring programs are needed to evaluate the cumulative success of current policies and programs and identifying potential problems before they become widespread or irreversible (Nusser and Goebel, 1997; Nusser et al., 1998; Urquhart et al., 1998). The Alaska Department of Environmental Conservation (ADEC) Alaska Monitoring and Assessment Program (AKMAP) is adapting the U. S. Environmental Protection Agency's (EPA) Environmental Monitoring and Assessment Program (EMAP) statistical sampling survey approach to help meet the challenge of assessing Alaska's vast coastal waters (ADEC, 2005a and b; US EPA, 2010). AKMAP assessments have sampled a number of regions in Alaska but it will be years before resource managers can use "new" AKMAP data to understand trends and changes in status over time in most areas. Considering the high costs and logistical difficulties in conducting EMAP surveys in Alaska, it is critical to determine if we can "mine" historic data for *post hoc* environmental baseline EMAP assessments.

The Alaska Department of Environmental Conservation (ADEC) Division of Water Alaska Monitoring and Assessment Program (AKMAP) mission is to provide for assessments of Alaska's aquatic resources by information to resource managers to protect environmental resources and promoting sustainability for Alaska (ADEC, 2005a and b). A necessary ingredient for success in managing resources is appropriate environmental data and the poor availability of broad-scale, temporal data sets for Alaska hinders management efforts. There are numerous pre-existing data sets but loss of data over time, limited availability, and poor coordination of data collections procedures reduces their value for future monitoring efforts (Olsen et al., 1999). Highlighting the problem at hand, numerous marine environmental datasets have been collected by various agencies and others in monitoring the oil and gas development activities on Alaska's North Slope creating a poorly integrated array of physical and chemical data sets for the western Beaufort Sea (Naidu et al., 2001; Naidu et al., in press). A large quantity of older data is unavailable or lost in forgotten reports. A first step towards investigating uncoordinated historic datasets is the recovery and assimilation of the data into a common database. The existing baseline data can then be assessed to determine if it is of sufficient scope and quality to conduct temporal analyses including *post hoc* assessments of status and trends using Aquatic Resource Monitoring sampling survey methods (US EPA, 2010). Addressing this data gap and using EMAP assessment methods will help fulfill a key part of the State of Alaska's long term Water Quality Monitoring and Assessment Strategy that guides the Department of Environmental Conservation's (DEC) stewardship of Alaska's coastal waters.

The present study is a pilot project to evaluate the feasibility of conducting *post hoc* EMAP assessment using historic long-term marine environmental datasets and will provide insights in trends of sediment variables within the western Beaufort Sea. The objectives of this study were to compile historic data to be made publicly available online and to perform an assessment of temporal trends. Data for the project were available from numerous technical reports and online data sets on which retrospective analysis using spatially-balanced sampling locations was performed. Success of retrospective methods of this project will offer scalability and transferability to other regions in the United States that have significant existing environmental data sets that have not been utilized by EPA for EMAP status and trends assessment. In addition, an assessment of this historic data, by and of itself is important to determining the most applicable and efficient techniques for an Arctic Coastal assessment.

METHODS

Data Recovery

Our approach for this pilot project was to search for and assimilate data from the long-term (30 + years) marine environmental monitoring and research study datasets for the western Beaufort Sea. Data was recovered from reports retained by researchers at the University of Alaska Fairbanks and online sources (Table 1). The data recovery process included:

- Compilation of data from online sources and available technical reports.
- Researching datasets to establish what datasets, e.g. water chemistry, sediment metals, are complete enough to provide a time series from the 1970's to present.
- Selection of datasets applicable to the general EMAP sediment quality analysis approach, e.g., water chemistry, benthic communities, sediment chemistry. (Data sets that were too local or proprietary were not considered.)

- Review of data QA/QC to determine if the data are of sufficient quality for use in the *post hoc* EMAP status and trends assessment (Appendix I).
- Preparation of meta-data for these data sets to be provided with the final report and electronic distribution venues including EPA's Office of Water STOrage and RETrieval (STORET) database and the Geographic Information Network of Alaska (GINA).

The region of interest for this pilot project covers estuaries and coastal waters of the western Beaufort Sea from Point Barrow eastward to Demarcation Point, including both State and Federal waters (Fig. 1). The area of interest covers approximately 24,000 km^2.

Retrospective Analysis using EMAP methods

The intention of the project was to use a probabilistic sampling design based on the generalized random tessellation survey (GRTS) design (Stevens and Olsen, 2004) to perform a retrospective analysis of the historical data using EMAP-style summary methods. The EMAP approach was used estimate summary statistics for each decade from 1970 to present. The EMAP national survey goal for precision is ±12% at 90% confidence for population proportion estimates (US EPA, 2001; US EPA, 2007). Statistically, 50 EMAP sample sites will provide this level of precision. Thus, fifty sites were generated with the GRTS design for each decade. Initially, sampling of the historic data using a procedure such a nearest-neighbor approach was planned. Unfortunately, the historic data were spatially sparse with very low numbers of unique sampling locations in some decades which was problematic for *post hoc* sampling with EMAP spatially-balanced statistical methods. Thus, an alternate approach was developed where geostatistical methods (Cressie, 1993) were applied to simulate predicted values for the variable of interest for the GRTS sample locations. Shifting support from year-to-year (changing numbers of stations and station locations) is always a problem in retrospective analyses and the geostatistical method is robust to varying sample locations.

The following graphics illustrate the procedure for sampling and geostatistical modeling. The first step is to determine suitable boundaries (spatial polygon) for study and the area that lies between the western Beaufort Sea coastline and the Alaska State boundary was selected (Fig. 1). The boundaries for retrospective analysis were reduced from the boundaries of the whole study area to encompass the region with enough data over the decades to make reliable geostatistical predictions for an EMAP assessment of the western Beaufort Sea. The study area was not stratified into subregions for this project. The next step was to use the spsurvey library for the statistical package R (R Development Core Team, 2009) to generate GRTS samples within the polygon (Fig. 2). Following generation of the GRTS sample, a geostatistical model was developed for each decade for the variable of interest, by way of example we present details for percent mud (Fig. 3), and predictions made for the GRTS locations. The libraries geoR (Ribiero and Diggle, 2001) and gstat (Pebesma, 2004; Bivand et al., 2008) were used for geostatistical analyses in R. Spatial correlations for percent mud, copper, and zinc were modeled using the spherical model while chromium required the exponential model. The R library gstat includes a function for simulating random data with the geospatial characteristics of the raw data and simulated data from this R library was used to generate summary statistics and cumulative distribution functions (CDF). The kriging routine in the gstat library simulates normal data so nonnormal data required transformation prior to simulation. The distribution of percent mud required an arcsin(square-root(x))-transformation to simulate and chromium required a log(x)-transformation. Copper and zinc concentrations were sufficiently normal so no transformations were applied. The data for mud were back-transformed using a $\sin(x)^2$ transformation and data for chromium were back-transformed as e^x. The back-transformed, simulated data were used for the retrospective analyses.

The EMAP-style status and trends assessment relies on calculation of summary statistics and cumulative distribution functions and comparisons to indicators of ecological health. Cumulative distribution functions (CDF) are plots of the cumulative value of sorted variables and are one method of summarizing probability distributions. CDFs are useful for describing features of variables in that extreme data points extend a CDF to one side or the other resulting in a visually-skewed plot. Highly skewed data may represent a log-normally distributed value but may also indicate areas where sediments are compromised. In the EMAP method, CDFs are generated that estimate the proportion of habitat of the study area with values equal to or less than a specific value. Comparison of summary statistics to sediment quality criteria (SQC) provides the basis for determining the proportion of sediments in good, fair, or poor condition relative to the SQCs. Long et al. (1995, 1998) have proposed guidelines to determine the potential for adverse effects by selected metals in sediment on resident marine benthic organisms and demersal fish. Based upon empirical analysis of a broad database consisting of equilibrium-partitioning modeling, laboratory bioassays and field studies on total sediments, Long et al.

(1995, 1998) developed two SQC values, an effects range-low (ERL) and an effects range-medium (ERM), by evaluating biological effects on numerous benthic taxa associated with selected trace metals and hydrocarbons in gross sediments. The SQCs for this study were the ERL and ERM (Long et al., 1995; Buchman, 2008).

Statistical comparisons of the CDFs between decades were performed using the cdf.test routine of the spsurvey library for R (Kincaid, 2000). The cdf.test routine provides a goodness-of-fit-test for comparing CDFs with two choices for adjustment to the degrees of freedom. The Wald’s test with the Satterwaite approximation to the degrees of freedom was selected here for CDF comparisons. The Bonferroni correction was applied to comparisons for each variable as $\alpha^* = \alpha / k$ where k = the number of comparisons made. For the six pairwise comparisons made between decades, the adjusted degrees of freedom applied to tests for each variable was $\alpha^* = 0.5/6 = 0.0083$. Statistical tests for distributions test the hypothesis H_0: the distributions are the same vs. H_a: the distributions are different and a difference in CDFs between two decades indicates a change in distribution but not necessarily a change in significant change in a standard summary statistics such as the mean value.

Bootstrapping was applied to determine summary statistics and CDF plots for the original data as a basis for evaluating the geostatistical simulations. In bootstrapping, data are randomly resampled from the raw data (with replacement) to determine standard errors and confidence intervals for summary statistics (Efron and Tibshirani, 1993). Bootstrapping is appropriate for this study as the varying methods, sampling locations, and spatial and temporal correlations represent deviations from assumptions of independence, a situation where randomization methods are useful (Manly, 1997). Here, the summary statistics and CDF plots from bootstrapping are compared to the results of the geostatistical modeling approach. Assuming that the simulation based on spatial correlation models provides an adequate representation of the data, the confidence intervals from simulations should be similar to the bootstrapped confidence intervals, or at least not diverge strongly from, the confidence intervals of the raw data. Large differences in confidence intervals would suggest a need to adjust the simulation models.

For the most part, the distributions of back-transformed simulated data were similar to those of the historic data (Fig. 4). The percent mud data appear to be uniformly distributed and the distributions of the simulated data were not unlike those expected for random, uniform data. For a uniform distribution, the histogram will show values fluctuating about a mean value and although a peak or skewness may occur, the overall trend with resampling will be essentially flat. That is what the histograms for percent mud reveal. The confidence intervals for simulated data (for a sample equal to the number of unique locations available) for a percent mud were larger than those from boostrapped samples but were not unreasonable although the CDF of the original data does approach the 95% confidence intervals for some years at the lower and upper tails (Fig. 5). Similar results were obtained for the metals investigated.

RESULTS

Historic Data Recovery

We were able to acquire data from 5 decades, 1960 to 2000, covering the western Beaufort Sea from Point Barrow eastward to the Demarcation Point. The data collected include sediment grain-size, trace metals concentrations, and to a limited extent, some chemical information such as total of selected aromatic hydrocarbons (PAH) and total organic carbon (TOC) (Table 1). The data encompass 78 variables for a total of 112 stations over 5 decades. Data for the 1960s, however, were extremely limited and that data were not included in further analyses. Records for four variables used in EMAP analyses, percent mud, copper, chromium, and zinc, were complete enough to perform a retrospective analysis. (Data records for the other variables compiled were incomplete for a retrospective analysis and the variables were not analyzed.) However, the spatial density of the data was low so geostatistical methods were applied, as described above, to perform the retrospective analysis. Although not presented here, the entire data collection will be submitted to the EPA, ADEC, and GINA. Limited biological information (abundance of benthic infauna from soft sediments in the Prudhoe Bay area) was available from the early 1970's and 1980's and is summarized here.

EMAP-Style Retrospective Analysis

Sediment percent mud (percent silt+clay) ranged from 0.1% to 99.9% in the database from 1970 to 2000 (Table 2). ANOVA results indicate significantly differences ($\alpha = 0.05$) among years ($p = 0.0017$) with greater percent mud in 1970 than in later years (Fig. 6). The values for one simulation of percent mud were similar to the raw data ranging from 0.0% to 100% (Table 2). Comparisons of CDF's using the Wald's test with the Satterthwaite-corrected degrees of freedom indicate that the CDF for 1970 is different from the CDF of 2000 at the

Bonferroni-corrected significance level of $\alpha^* = 0.0083$ (Fig. 7). The CDF for 1970 indicates a higher proportion of area with muddy sediments (50% of sediments in the study area have ≤ 60% mud) as it is flatter while the CDF for 2000 indicates lower percent mud (50% of the study area has ≤ 30% mud in sediments) (Fig. 7).

Sediment copper concentrations ranged from 3 to 55.3 ug g^{-1} (Table 3). The values for one simulation of copper concentrations ranged from 0.5 to 41.6 ug g^{-1}. No significant differences in the mean concentrations of copper were noted among decades from ANOVA ($p = 0.0695$) though copper value was slightly elevated in 1980 (Fig. 8). Comparisons of CDFs using the Wald's test indicate that the CDF for 1980 is significantly different ($\alpha^* = 0.0083$) from the CDF of 2000 (Fig. 9). Copper was higher in 1980 with 50% of the study area estimated as having concentrations of ≤ 23 ug g^{-1} and 50% of the study area in 2000 having ≤ 17 ug g^{-1} (Fig. 9). The percentage of copper concentrations exceeding the ERL but not the ERM in the Beaufort Sea database ranged from 8 to 28%. The percentage of area between the ERL and ERM in the simulated data ranged from 2 to 8% of the total area (Table 3).

Chromium concentrations ranged from a minimum of 12.7 to a maximum of 1118 ug g^{-1} (Table 4). ANOVA indicated significant differences in the mean concentrations of chromium among decades ($p = 0.0027$) with chromium elevated in 1980 relative to the other years (Fig. 10). Additionally, comparisons of CDFs indicated that the 1980 CDF was significantly different ($\alpha^* = 0.0083$) from the CDFs for 1970, 1990, and 2000 (Fig. 11). The CDFs indicate that roughly 50% of the study area in 1980 had chromium concentrations of ≤ 80 ug g^{-1} and 50% of the study area had ≤ 50 ug g^{-1} in 1970, 1990, and 2000 (Fig. 11). The percentage of chromium values greater than the ERL ranged from 8 to 96% considering the entire Beaufort Sea database, and 2% of the values exceeded the ERM and that was restricted to 1970 (Table 4). Based on the simulated data, none of the predicted sediments exceeded the ERM and between 16% to 52% of the sediments exceeded the ERL.

The concentrations of zinc in Beaufort Sea sediments ranged from 14 to 171 ug g^{-1} and from 4.6 to 145.7 ug g^{-1} in the simulated data (Table 5). Comparisons between decades using ANOVA indicated significant differences in the mean concentrations ($p < 0.001$) with 1980 having higher zinc concentrations than the other years (Fig. 12). The CDF for 1980 was significantly different ($\alpha^* = 0.0083$) from the CDF for 2000 (Figure 13). The CDFs indicate that roughly 50% of the study area in 1980 had zinc concentrations of ≤ 80 ug g^{-1} and 50% of the study area in 2000 had ≤ 70 ug g^{-1} (Fig. 11). The percentage of zinc concentration values in the Beaufort Sea database exceeding the ERL and ERM ranged from 2 to 4% and the percentage of area less than the ERL in the simulated data was 100% for all decades (Table 5).

The biological data were inadequate for an EMAP-style analysis so the data are summarized here. The data comprise species composition and counts from 147 nearshore sampling locations (not all unique) in Prudhoe Bay (Fig. 14). Seventeen sites were sampled in August 1974, 72 in August and September of 1976, 34 in August 1977, and 22 in July 1981. Average abundance ranged from 843 to 3,136 ind. m^{-2} for each year (Table 6 and Fig. 15) and abundance increased with depth for all years sampled. The fauna of the study area were dominated by polychaete worms including *Ampharete vega*, the family Cirratulidae (*Cirratulus cirratulis*, Chaetozone *setosa*, and *Tharyx* sp.), and the Family Spionidae (*Prionospio cirrifera* and *Spio filicornis*) (Table 7). The bivalve *Cytrodaria kurriana* was also abundant in some years.

DISCUSSION

The objectives of the Advanced Monitoring Initiative were two-fold. The first objective was to compile and make available historic data comprising a suite of sediment trace metals and granulometry and benthic faunal organisms from the Beaufort Sea. As a result of this study, sediment chemistry and grain-size data spanning five decades and 112 unique sampling locations will become publicly available for investigators working in the study area through EPA's STORET and other sites. Biological data collected in Prudhoe Bay from 1974 to 1981 will also be available. The second objective was to analyze the data using EMAP methods to determine the ecological status of the Beaufort Sea. Four variables, percent mud, and sediment concentrations of copper, chromium, and zinc, were sampled with the EMAP spatially-balanced sampling design employing geostatistical methods to simulate the historic, spatially-correlated data.

The retrospective analysis of the four variables indicated no temporal trend (i.e., net increasing or decreasing trend) but it is clearly indicated that 1980 was punctuated by significantly higher mean concentrations of copper ($\alpha = 0.10$) and chromium and zinc ($\alpha = 0.05$) in sediments. It is possible that increased mud content in the 1980 sediments resulted in higher contents of copper, chromium and zinc, because finer particles have greater potential capacity to sequester the metals by adsorption and/or metal-clay complex formation. However, this is not demonstrated by a parallel increase in mud in 1980. The other possibility is that there was an episodic increased flux and deposition of the three metals from the terrestrial natural source to the marine study area. This explanation also seems unlikely as there is no evidence to support an episodic flux. We explain the 1980 anomaly in sediment copper, chromium and zinc as reflecting higher input of the metals from petroleum-related industrial activities. In this context, it is interesting to note that the higher mean concentrations of the above metals are consistent with significant spikes in the levels of several metals (V, Cr, Cu, Ni, Zn, As, Cd, Pb and methyl Hg) in 1980 as demonstrated in the stratigraphy of a ^{210}Pb-based dated sediment core from Prudhoe Bay, north arctic Alaska (Naidu et al., 2001; Naidu et al., in press). The more intense (several fold) exploratory drilling activities in 1980s relative to other years, 1940-2001 (National Academy of Sciences, 2003), would result in higher discharges of copper, chromium, zinc, and other contaminants into the environment and, thus, accumulation of the metals in the sediments of the study area. The three metals evaluated in the present study are important trace constituents in the additives entrained in drilling fluids in petroleum exploration in north arctic Alaska and would be expected to increase with greater drilling effort (Boehm et al.,1987; National Academy of Sciences, 2003). Thus, the overall discharge of higher concentrations of the metals in drilling effluents in the past resulted in the higher fluxes of the three metals to sediments, and greater concentrations, in 1980.

Although a moderate percentage of sediments in the Beaufort Sea have mean concentrations of copper, chromium and zinc that exceeded the ERL and for chromium, the ERM, the overall ecological status of the Beaufort Sea sediments, in context of the three metal contaminants, was apparently good. Presumably, the trace metal concentrations in 1970 reflect the natural variability in sediment chemistry in the dynamic nearshore environment of the Beaufort Sea resulting from local and regional processes and spatial trends (Naidu et al., in press). The data suggests the trace metals concentrations in sediments of the western Beaufort Sea sampled in 1990 and 2000 were also within the range of natural variability. The mean concentrations of both chromium and zinc were significantly elevated in 1980 as was copper but a higher level of significance ($\alpha = 0.10$) and this may reflect a difference in historic drilling patterns, as discussed above. One extremely high value for chromium in 1970, 1,118 ug g^{-1}, resulted in exceedence of the ERM for this trace metal. Whereas the percentage of area estimated to lie between the ERL and ERM for copper and zinc ranged from 0 to 8%, the estimated percentage for chromium ranged between 16 and 52%. The average sediment concentrations reported here are slightly higher than values reported by Naidu et al. (in press) approaching the range of means associated with anthropogenic activities (Snyder-Conn et al., 1990). The higher values in this study may reflect a bias towards sampling at sites of human activity in the long-term monitoring data set compiled here as opposed to the broader focus of Naidu et al. (in press).

Methodology

The original intent of the retrospective analyses in the AMI pilot study was to randomly sample the historic database using spatially-balanced designs. The decision to use geostatistics to develop predictive models was data-dependent based solely on the sample size and distributions of sampling location among years. Sampling the data using the nearest neighbor to a GRTS sampling location or using the value(s) that fall within a specified distance of a GRTS samples was considered. Unfortunately, even with a minimum of 30 points, many nearest neighbors to the GRTS sampling locations would have been very far way and most of the raw data would have been reused - the density of sampling locations was too limited to allow a direct sampling. Additionally, none of the studies in compiled data from the western Beaufort Sea were identified as a probabilistic design limiting inferences. To resolve the sparse data problem and the lack of a random sample, geostatistical modeling was used to simulate data for the EMAP-style analysis. In the context of the present study, strengths of geostatistical modeling include the ability for data from different sampling designs to be incorporated into data sets and the method is robust to inclusion of varying locations (Cressie, 1993). The models generated are only as detailed as the data provided and in the present study, large scale trends could reasonably be predicted. The more extensive the data set, the better the model predictions will be. The EMAP approach to sampling relies on broad-scale random sampling to detect regional trends and in that context, the geostatistical approach taken here appears to be a reasonable first pass at elucidating temporal trends in the historic data with EMAP methods.

The simulated data compared well to data from the Beaufort Sea database as the data distributions, means, and standard deviations were reasonably similar. The simulations of maximum values were reasonably consistent with the raw data as summary measures were similar but there were fewer exceedances of the ERL in the simulated data, as compared to the raw data. This is not unexpected with simulated data since extreme data points tend to be smoothed when making model predictions. Additionally, the simulation of the data using geostatistical methods is strongly influenced by the density and characteristics of the locations sampled. Sampling artifacts due to varying support (changing station locations between years) will be important. Overall, however, the simulated data approximated the raw data quite well.

A single best method for retrospective analysis of historic data does not exist as each case is unique to the available data and purpose of each study. Multiple options are available and opinions will differ as to the best method. We understand that the method presented here may not be the best or accepted by other practitioners but it is a reasonable and comparatively simple approach to deal with the specific problem presented by the compiled data. Rather than being considered as the approach to use, we hope that this study can contribute to conversations that can refine methods for compiling and analyzing uncoordinated, historical data sets, a process that can be difficult as data often come from different sampling designs (Olsen et al., 1999).

Data Gaps

A number of key data gaps can be identified in the compiled databases. The data gaps represent not only the absence of data but poorly aligned objectives of multiple studies, missing links to other investigations, and no data integration.

Monitoring of sediments is critical to understanding the influences of human activities in the marine environment. Monitoring may include evaluation of other ecosystem components but measurement of change in sediment quality provides the critical link between anthropogenic stressors and ecosystem changes. Worldwide, environmental monitoring studies focus on sediment contaminant burdens and the fauna which are directly influenced by contaminants (e.g., Olsgard and Gray, 1995). The absence of biological monitoring in the western Beaufort Sea is an oversight that hinders direct assessment of potential ecosystem alterations by human activities. As a result of the absence of biological data, a critical link is broken in understanding the relationships between sediments, sediment-dwelling fauna, bottom-feeding predators, higher trophic levels, and ultimately, human health. A broader, ecologically-focused plan for monitoring is encouraged requiring data collection at both local and regional scales sampling all appropriate ecological components.

Integration of data from multiple sources is a daunting task. Challenges arise in maintaining consistent sampling designs, data formats, availability, and reliability (Olsen et al., 1999). Due to the absence of long-term data storage facilities in the past and/or easily accessed data portals, older data sets have been lost. There is a critical need, however, for access to older data sets, such as those made available from this study and the lack of a data storage site and data portal represents another data gap. Some portals are available but they can be hard to find, data may be difficult to access, or in the case of GIS-based sites, require high sophistication for acquiring and understanding the data. A data portal for access to data formats would be useful to a broad range of scientists.

The lack of consistency in variables measured, the techniques for measuring data, and sites sampled can result in incomparable data and data gaps (Olsen et al., 1999). Such problems can be resolved by establishing region-wide data collection standards specific methodologies, summary measures, and endpoints. For example, the lack of consistency in PAH calculations can be problematic due to changes in beliefs about important variables. Sediment quality criteria (including ERL and ERM) for the total PAH calculation are often based on parent species and comparisons of these criteria (Long et al., 1995, 1998), or historic PAH calculations (Naidu et al., in press), to total PAH based on homolog species would be incorrect. Inconsistencies in summary statistic calculations are an issue in monitoring elsewhere in Alaska (Savoie et al., 2006; Payne et al., 2008; Blanchard et al., 2010). Local-scale monitoring consistent with the methods for regional sampling would contribute greatly to understanding spatial and temporal variability and should be required of resource users. Low power is often a problem leading to understatement of ecological effects and subsequent detrimental alterations and is a problem with managing marine systems (Peterman, 1990; Urquhart et al., 1998). Local-scale sampling would contribute to reducing problems with low power.

Recommendations for a Long-Term Integrated Plan in Alaska

Considerable costs have been incurred in environmental studies of Alaska waters, in this case the Beaufort Sea, to assess background conditions to assist in monitoring impacts from oil and gas resource development. The principal datasets used in our study are from the U.S. Department of Interior Mineral Management Environmental Studies Program that supports the offshore oil and gas-leasing program of the U.S. Department of the Interior (USDOI) in pursuit of national energy policies. These studies are typically targeted studies designed to provide MMS with information to monitor and assess potential impacts of oil and gas development. While studies are designed to meeting MMS project needs, sampling methodologies and resultant datasets are applicable to addressing regional scale issues or questions raised by non-governmental groups (Heinz Center, 2008) and federal/state agencies (ADEC, 2005a,b; US EPA, 2010). Some of these questions are:

- *How is the regional environment changing?*
- *Are the problems faced getting better or worse?*
- *Where are problems located?*
- *What new challenges are arising?*
- *Are government or private programs dealing effectively with these challenges?*
- *Can results be extrapolated to the regional resource population to estimate current status, trends, and changes in select indicators with known confidence?*
- *Do results provide estimates of geographic coverage and extent of regional ecological resources with known confidence?*
- *Are there associations between select indicators of natural and human stresses and indicators of the condition of ecological resource?*

As discussed in this report, probabilistic survey sampling can provide reliable, unbiased estimates of regional ecological condition. The GRTS design used for the probabilistic sampling in the present study is one of a number of probabilistic designs and provides spatially-balanced samples and unbiased estimates for sampling large regions (Stevens and Olsen, 2004). The use of targeted (fixed) vs. probabilistic (random) designs depends on the goals of each project with fixed stations providing greater power but spatially-limited inferences (Thompson, 1992; Van der Meer, 1997). Long-term sampling of fixed locations provides the means to detect long-term environmental change and should be a focus of local sampling but the range of inferences are limited to the chosen locations whereas random sites (Urquhart et al., 1998; McDonald, 2003; Blanchard et al., 2010). Difficulties arise when compiling data from various sampling designs to gain insights into regional trends (Olsen et al., 1999). Comparisons of targeted and probabilistic survey sampling documented that regional extrapolation of non-probabilistic results cannot provide unbiased estimates of regional condition (Peterson et al., 1999; Hawkins et al., 2008). Our attempt to use the historic datasets for this region to provide a methodology for a reasonable *post hoc* survey analysis, while having some success, clearly indicated the need for a long-term reasoned multi-faceted monitoring effort.

As has been recognized in the past 20 years, resource management needs go beyond any one agency, local government, or public interest group mission requiring an integrated multi-resource and multi-disciplinary approach (US EPA, 2001; ADEC, 2005a and b; NWQMC, 2010). We argue that it is in the interest of the State of Alaska, the Federal Government, local governments, interest groups that a strong integrated long-term monitoring and assessment program (encompassing targeted sampling, probabilistic survey sampling and predictive modeling based on consistent, ecosystem-based indicators) is needed to protect and ensure the diverse uses of Alaska's aquatic resources are maintained. The efforts of the North Slope Science Initiative, Alaska Ocean Observing System, and the ADEC Water Quality Monitoring Strategy are steps in the right direction for evaluating Alaskan aquatic resources.

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Tables

Table 1. Summary of datasets recovered.

Reference	Year(s)	Variables	No. Stations
Naidu et al., 1982; Kinney et al., 1971; Alexander et al., 1974; Feder et al., 1976	1969, 1970, 1972,1973, 1974, 1975, 1977, 1980	Grain size, metals, clay mineralogy	99
Feder et al., 1976	1974	Benthic fauna, grain size, hydrocarbons in sediments	75
Hufford et al., 1974 (WEBSEC) ; Naidu et al., 1981	1971	Grain size, metals, clay mineralogy	62
Grider et al., 1977	1976	Benthic fauna, coastal processes	23
Grider et al., 1978	1977	Benthic fauna	34
Sweeney, 1984	1977	Grain size, metals, clay mineralogy	41
Feder and Jewett, 1982	1981	Infauna	22
Mangarella et al., 1982	1981	Physical oceanography	41
Boehm et al., 1987	1984, 1985, 1986	Hydrocarbon, metals, grain size, organic content	39
Boehm et al., 1990	1989	Hydrocarbons in sediment and tissue, metals, grain size, organic content	48
Naidu et al, 2001	1997, 1999	Grain size, metals, hydrocarbons in sediments	21
Boehm et al., 2001	1999	Grain size, metals, hydrocarbons in sediments	45
Naidu et al., 2003	1999	Grain size, metals, hydrocarbons in sediments	5
Brown, J., 2005	2000, 2002	Hydrocarbons, metals, grain size (tissue and sediment)	29
Naidu et al., 2005 ; Naidu et al., 2006	2003	Grain size, metals, hydrocarbons in sediments	22
Trefry et al., 2009	2004, 2005	Grain size, metals	63

Table 2. Summary statistics for simulated percent mud for 1970, 1980, 1990, and 2000.

Original Data

Year	Min.	Med	Mean	Max.	SD
1970	1.5	64.7	57	98.6	28.4
1980	0.6	34.5	42.9	96	29.8
1990	1	33.4	43.3	98.8	34.1
2000	0.1	46	45.6	99.9	30.4

Simulated Data

Year	Min.	Med	Mean	Max.	SD
1970	9.3	56.4	59.1	99.8	28.3
1980	0.2	39.9	42	99.9	29.3
1990	0	42.3	48.4	100	33.5
2000	0	29.9	37.9	99.5	29.1

Table 3. Summary statistics for simulated sediment copper for 1970, 1980, 1990, and 2000. % < ERL = % exceeding the ERL, ERL<X <ERM = % exceeding the ERL and less than the ERM, and % > ERM = % exceeding the ERM. Copper ERL = 34 ug g^{-1} and Copper ERM = 270 ug g^{-1}.

Original Data

Year	Min.	Med	Mean	Max.	SD	% Values < ERL	ERL< X < ERM	% Values > ERM
1970	3	20	20.7	83	9.8	74	26	0
1980	13	24	23.8	40	5.1	92	8	0
1990	4	21.6	20.6	46.9	11.1	90	10	0
2000	3.9	20.9	21.8	55.3	11.6	72	28	0

Simulated Data

Year	Min.	Med	Mean	Max.	SD	% Area < ERL	ERL< X < ERM	% Area > ERM
1970	6.5	20.9	22.1	39.2	8.5	92	8	0
1980	10.7	22.8	22.7	36.9	5.4	98	2	0
1990	2.2	19.3	21	41.6	7.6	96	4	0
2000	0.5	17.4	17.4	38.2	7.2	98	2	0

Table 4. Summary statistics for simulated sediment chromium for 1970, 1980, 1990, and 2000. % < ERL = % exceeding the ERL, ERL<X <ERM = % exceeding the ERL and less than the ERM, and % > ERM = % exceeding the ERM. Chromium ERL = 81 ug g^{-1} and Copper ERM = 370 ug g^{-1}.

Original Data Year	Min.	Med	Mean	Max.	SD	% Values < ERL	ERL< X < ERM	% Values > ERM
1970	15	55	64.3	1118	86.8	58	40	2
1980	42	85	86.5	219	24.1	4	96	0
1990	12.7	56.8	57.2	133.9	24.3	84	16	0
2000	14.7	65.8	63.6	188	23.8	92	8	0

Simulated Data Year	Min.	Med	Mean	Max.	< ERL	% Area < ERM	ERL< X < ERM	% Area > ERM
1970	18.4	52.4	62.3	203.9	36.6	78	22	0
1980	34.9	82.7	85.4	130.1	20.4	48	52	0
1990	12.7	49.5	58	120	26.8	76	24	0
2000	17.6	52.5	54.4	126.2	27.2	84	16	0

Table 5. Summary statistics for simulated sediment zinc for 1970, 1980, 1990, and 2000. % < ERL = % exceeding the ERL, ERL<X <ERM = % exceeding the ERL and less than the ERM, and % > ERM = % exceeding the ERM. Zinc ERL = 150 ug g^{-1} and Copper ERM = 410 ug g^{-1}.

Original Data Year	Min.	Med	Mean	Max.	SD	% Values < ERL	ERL < X < ERM	% Values > ERM
1970	28	82	80.9	160	24.3	96	4	0
1980	53	100.5	99.9	171	18.5	98	2	0
1990	14	84	75.9	140	35.3	100	0	0
2000	15	79.5	76.5	145	27.8	100	0	0

Simulated Data Year	Min.	Med	Mean	Max.	<ERM	% Area > ERM	ERL < X < ERM	% Area > ERM
1970	28.9	83.4	80.9	145.7	27.2	100	0	0
1980	42.6	85	86.4	139.2	19.8	100	0	0
1990	4.6	70.7	72	147	28.4	100	0	0
2000	8.2	66.7	67.6	126.5	24.5	100	0	0

Table 6. Average abundance and standard deviation for each sampling period from Prudhoe Bay, Alaska, 1974-1981. Average abundance is presented for all stations within years combined and by selected depth zones.

			All			≤ 1.5 m	
Year	Month	Mean	SD	n	Mean	SD	n
1974	August	1924	1845	15	1151	696	11
1976	August	843	765	36	355	261	12
1976	September	765	687	36	373	225	14
1977	August	1932	1598	34	938	704	9
1981	July	3136	3087	22	2357	816	2

			> 1.5 m			≥ 3 m	
Year	Month	Mean	SD	n	Mean	SD	n
1974	August	4049	2461	4			
1976	August	1141	923	18	927	382	6
1976	September	950	767	17	1237	806	5
1977	August	1671	734	19	4247	2376	6
1981	July	2523	3456	10	3905	3000	10

Table 7. Ranking by average abundance (ind. m^{-2}) of numerically-dominant taxa for Prudhoe Bay nearshore sites sampled 1974-1981.

Year	Month	Taxon	Abundance
1974	August	*Ampharete vega*	774
		Cirratulus cirratus	667
		Cyrtodaria kurriana	558
		Chone duneri	556
		Pontoporeia affinis	556
		Scolecolepides arctius	388
		Chaetozone setosa	156
		Saduria entomon	139
		Rhynchocoela	130
		Margarites helicinus	104
1976	August	*Chaetozone setosa*	389
		Ampharete vega	212
		Spio filicornis	136
		Cyrtodaria kurriana	125
		Oligochaeta	77
		Pontoporeia affinis	71
		Prionospio sp.	69
		Pontoporeia femorata	58
		Pygospio elegans	51
		Onisimus glacialis	51
1976	September	*Ampharete vega*	243
		Cyrtodaria kurriana	220
		Prionospio sp.	212
		Chaetozone setosa	140
		Tanaidacea	88
		Spio filicornis	86
		Pontoporeia affinis	63
		Pygospio elegans	62
		Liocyma fluctuosa	57
		Cossura sp.	55
1977	August	*Prionospio* sp.	641
		Chaetozone setosa	372
		Ampharete vega	268
		Scolecolepides sp.	268
		Pygospio elegans	176
		Tharyx sp.	161
		Cyrtodaria kurriana	159

Table 7. Continued.

Year	Month	Taxon	Abundance
1977	August	*Orbinia* sp.	154
		Oriopsis sp.	139
		Pontoporeia affinis	129
1981	July	*Prionospio cirrifera*	1148
		Tharyx sp.	718
		Pygospio elegans	686
		Ampharete vega	364
		Chaetozone setosa	202
		Chone sp.	145
		Pontoporeia femorata	135
		Liocyma fluctuosa	115
		Boreacola vadosus	104
		Aricidea minuta	102

Figures

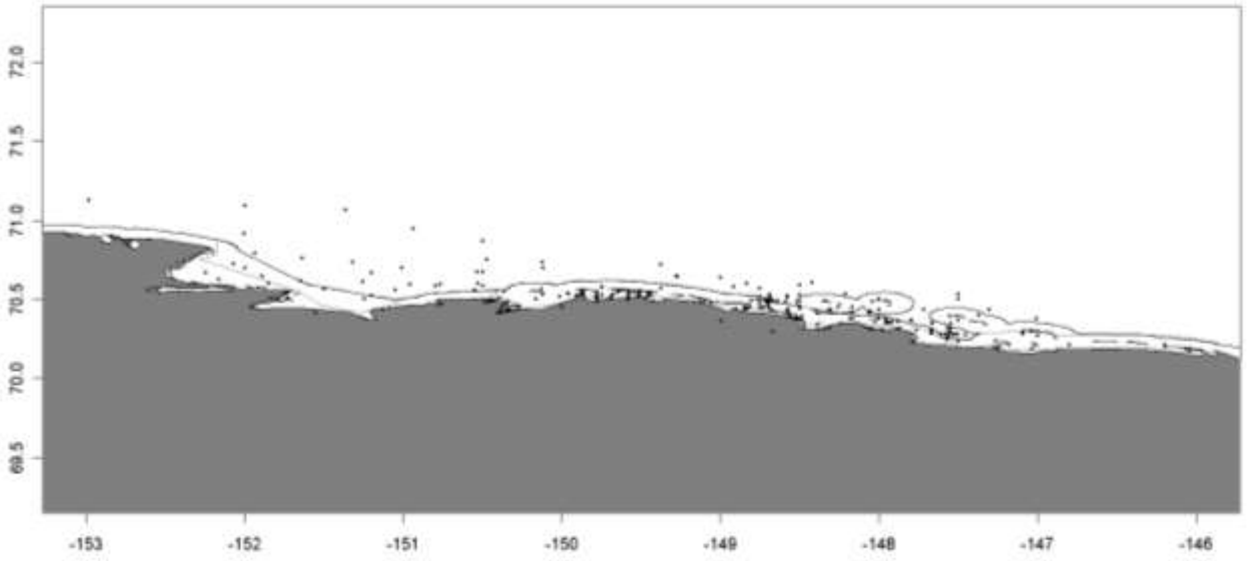

Figure 1. Map of the western Beaufort Sea with the Alaska State Boundary (solid line). The dotted line is the polygon for spatial predictions and the points are the locations of points in the database. The polygon for sampling follows the coastline and extends to the AK state boundary.

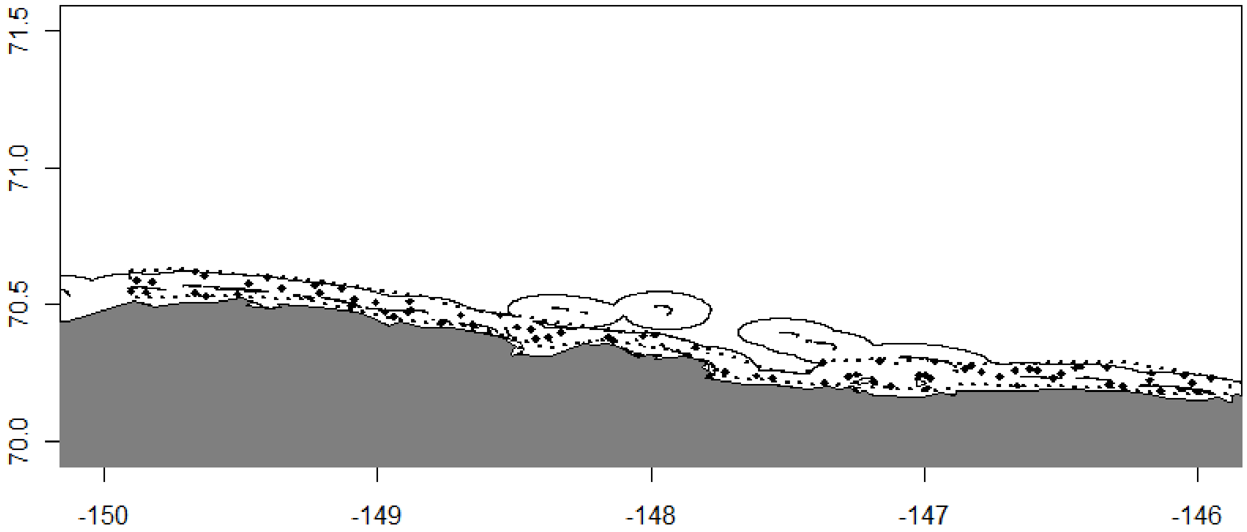

Figure 2. Map of the prediction region for the western Beaufort Sea with the Alaska State Boundary (solid line). The dotted line is the polygon for spatial predictions and the points are the locations of one collection of sampling points generated by one run of GRTS using the spsurvey library for R.

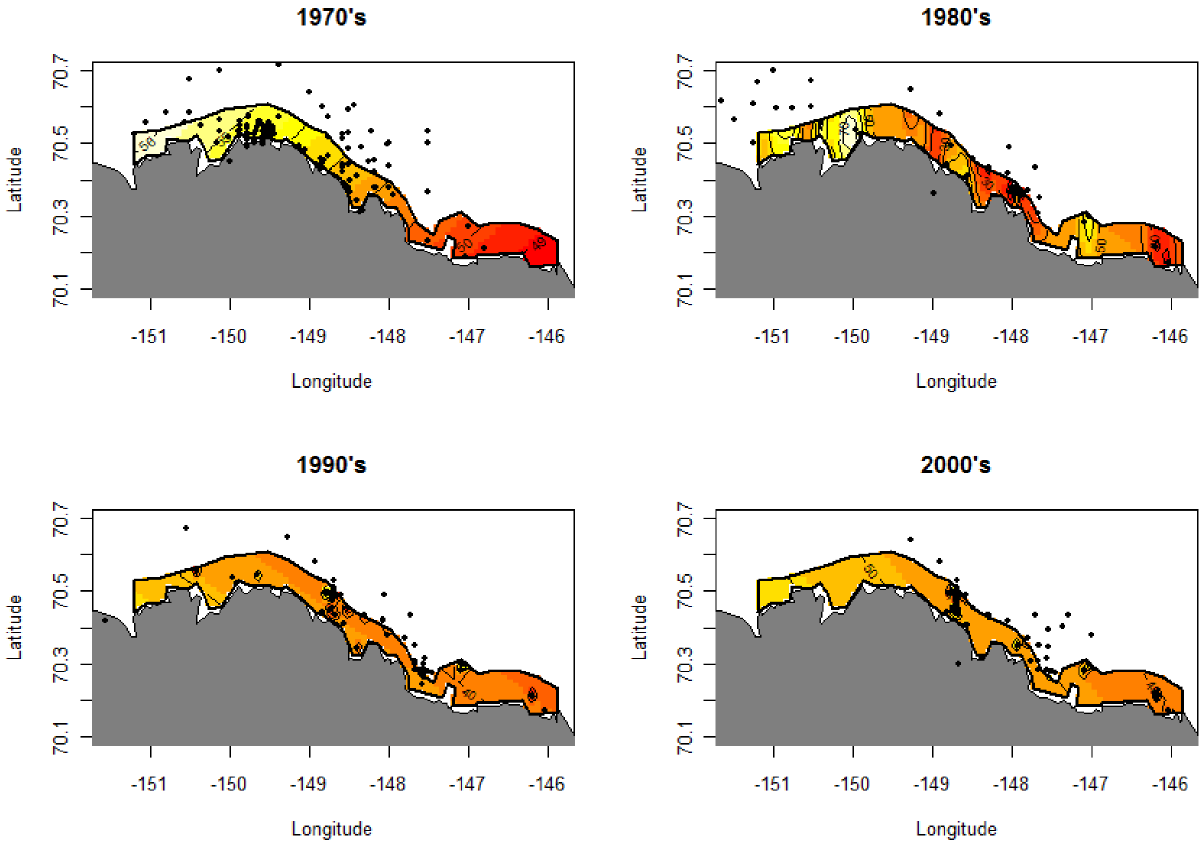

Figure 3. Geostatistical prediction contours for percent mud for the western Beaufort Sea for 1970, 1980, 1990, and 2000. The solid points are the locations of sampling points within each decade. The sampling polygon used in spsurvey is the solid line.

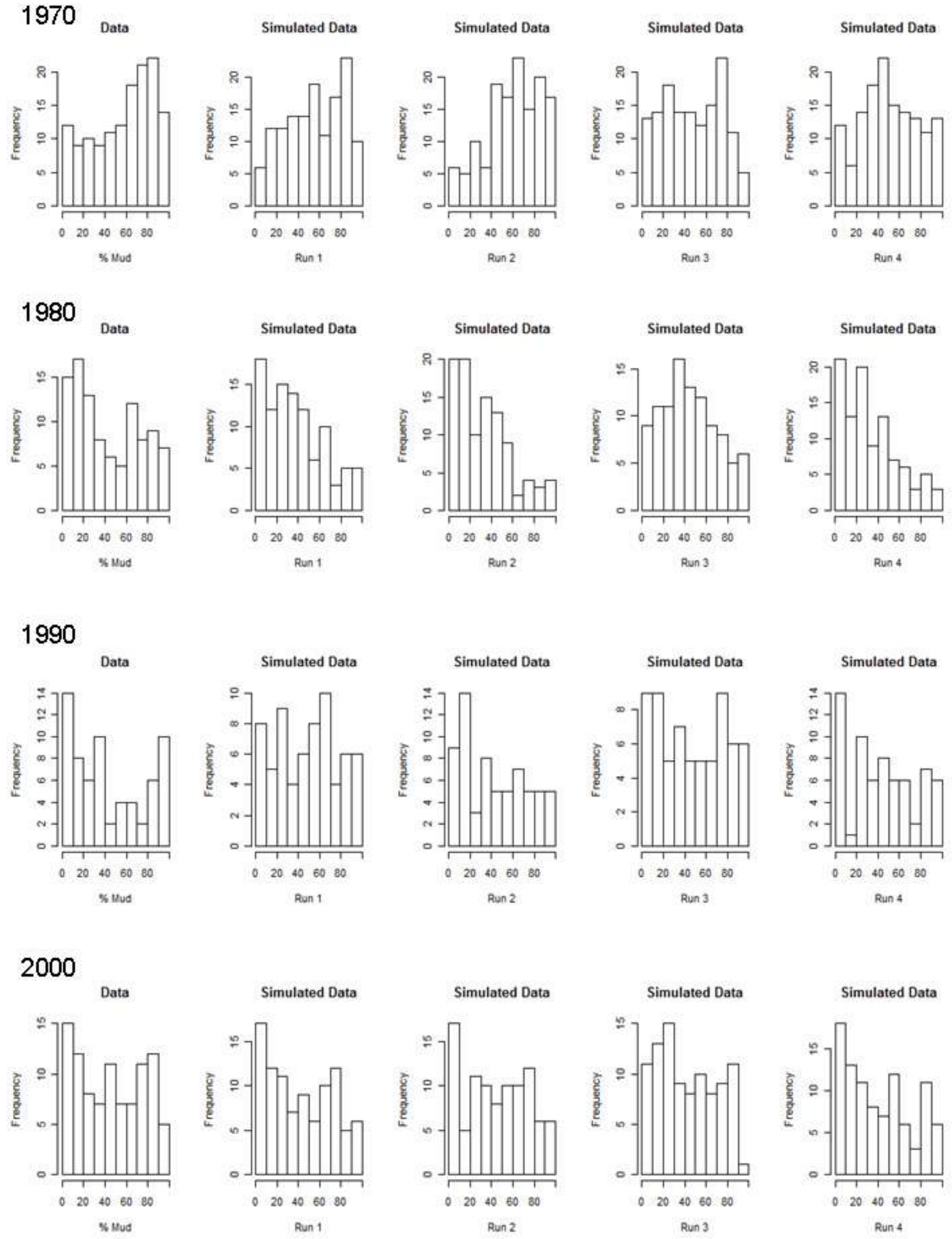

Figure 4. Histograms of percent mud for 1970, 1980, 1990, and 2000. Histograms were estimated for the raw data and 4 simulations from kriging.

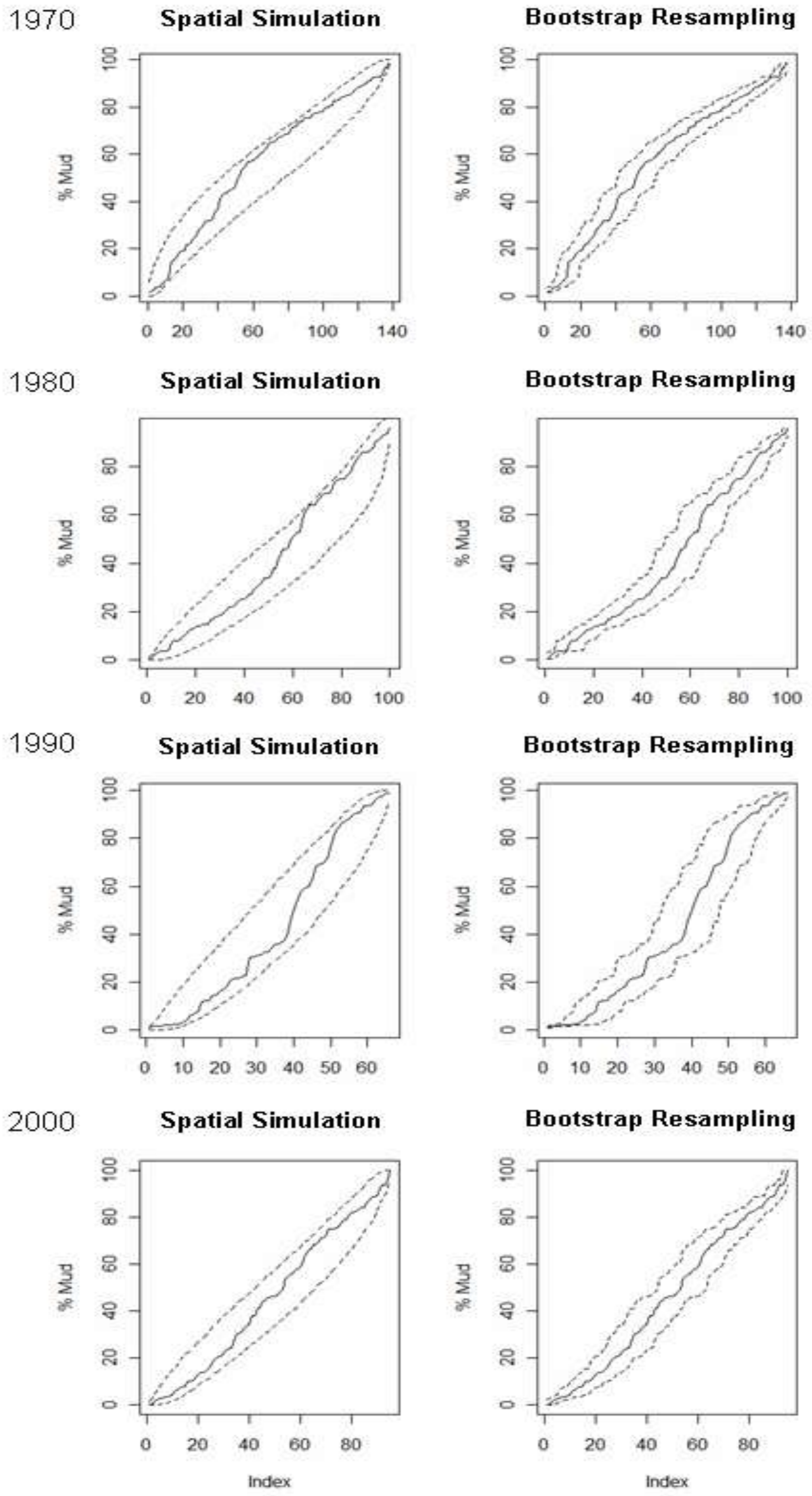

Figure 5. Cumulative distributions of percent mud and 95% confidence calculated from simulation and bootstrapping.

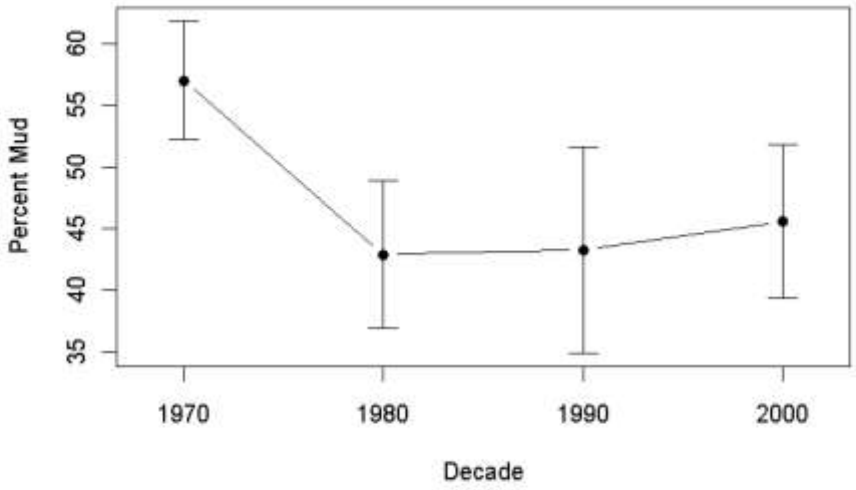

Figure 6. Line plot with 95% confidence intervals for percent mud by decade.

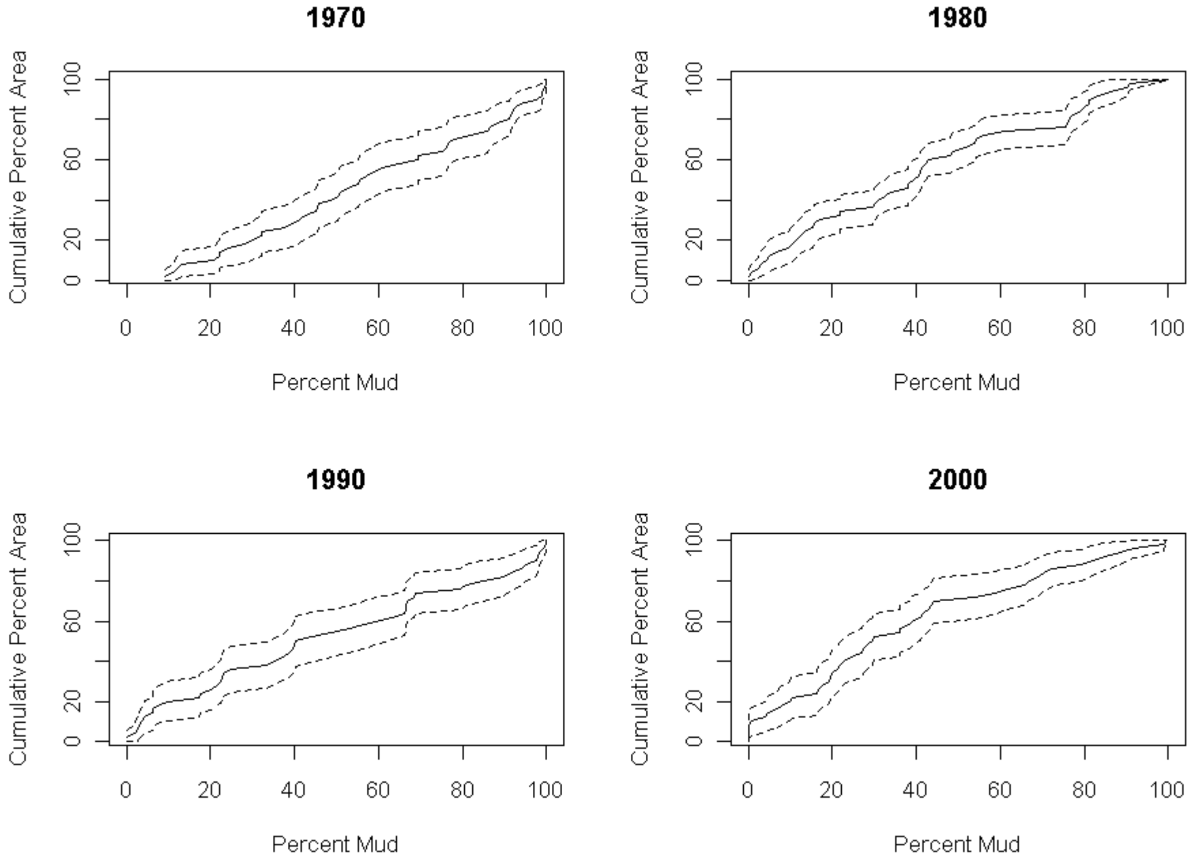

Figure 7. Cumulative percent of study area and 95% confidence intervals of Beaufort Sea coastal zone vs. percent mud from simulated sampling.

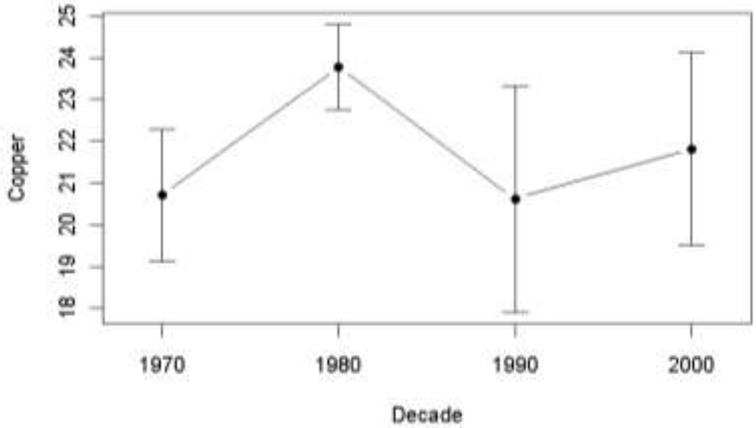

Figure 8. Line plot with 95% confidence intervals for copper by decade.

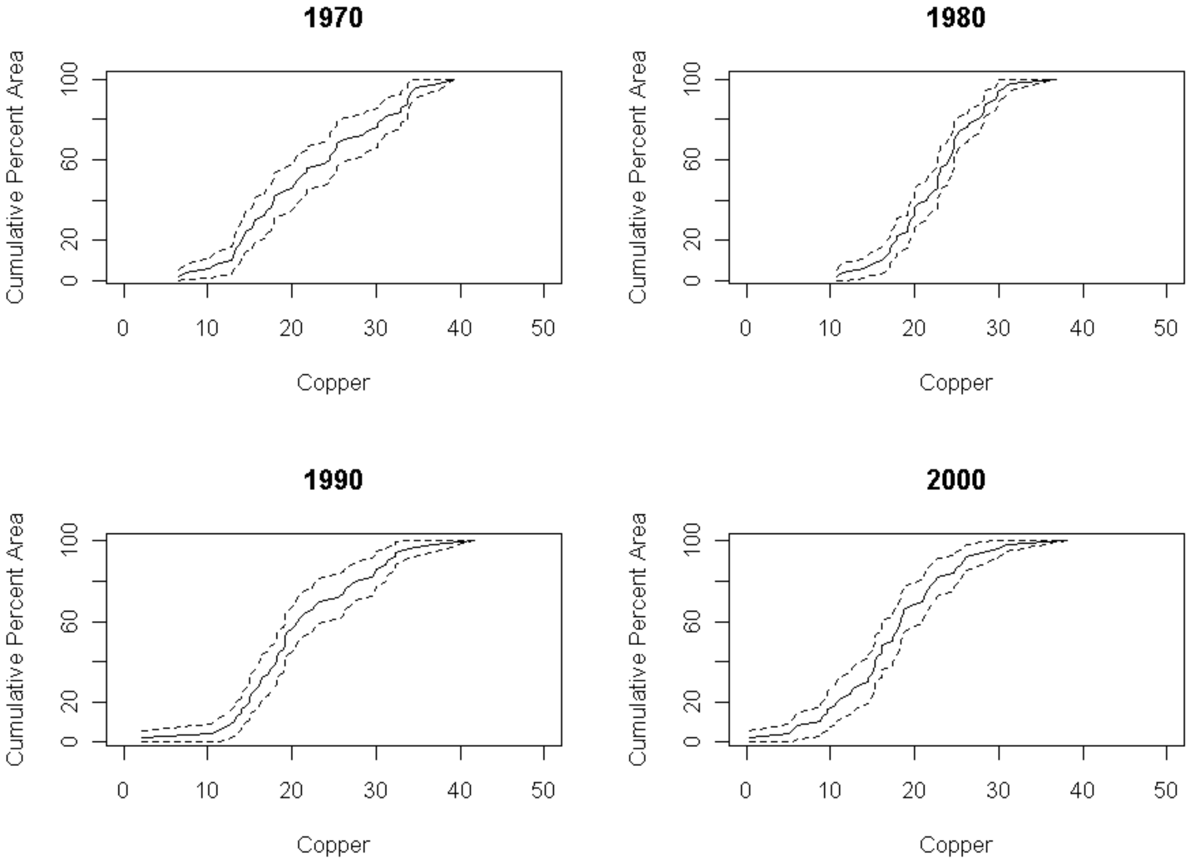

Figure 9. Cumulative percent of study area and 95% confidence intervals of Beaufort Sea coastal zone vs. copper (ug g^{-1}) from simulated sampling.

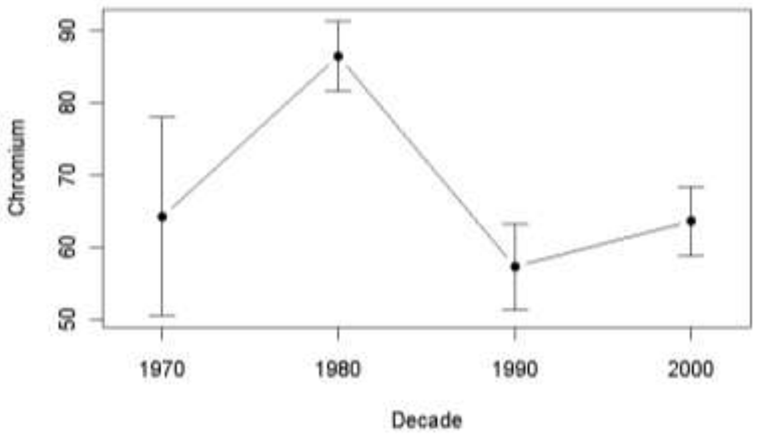

Figure 10. Line plot with 95% confidence intervals for chromium by decade.

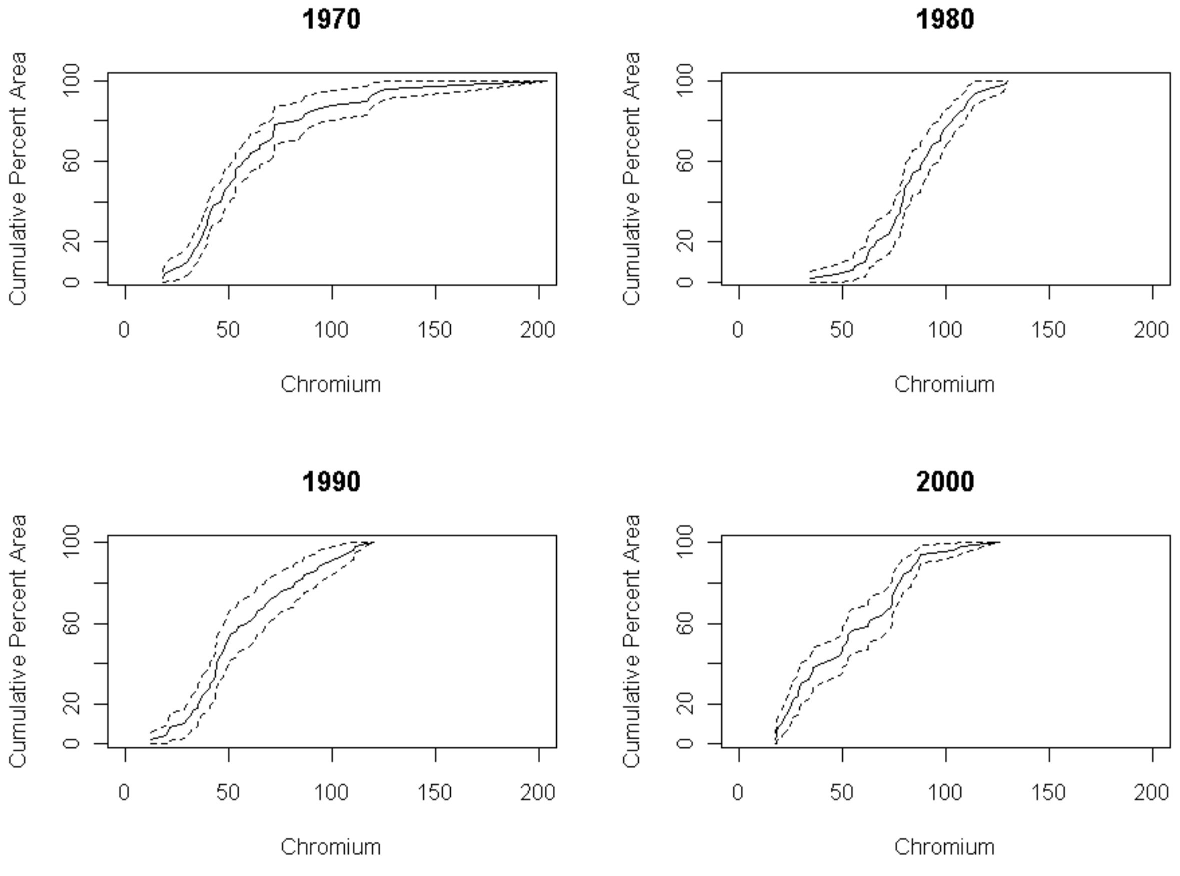

Figure 11. Cumulative percent of study area and 95% confidence intervals of Beaufort Sea coastal zone vs. chromium (ug g^{-1}) from simulated sampling.

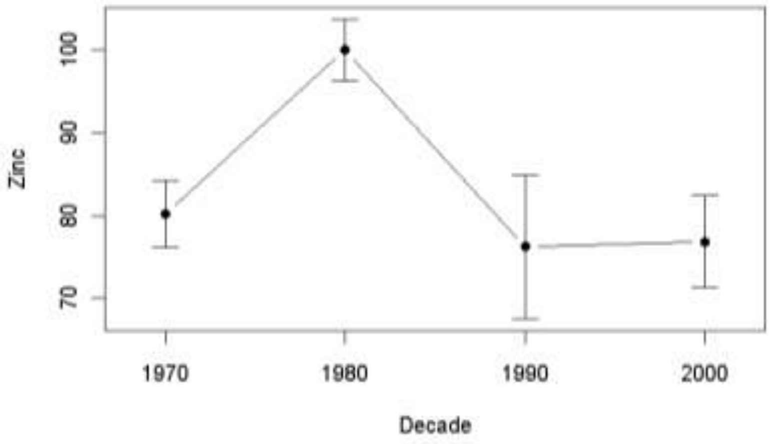

Figure 12. Line plot with 95% confidence intervals for zinc by decade.

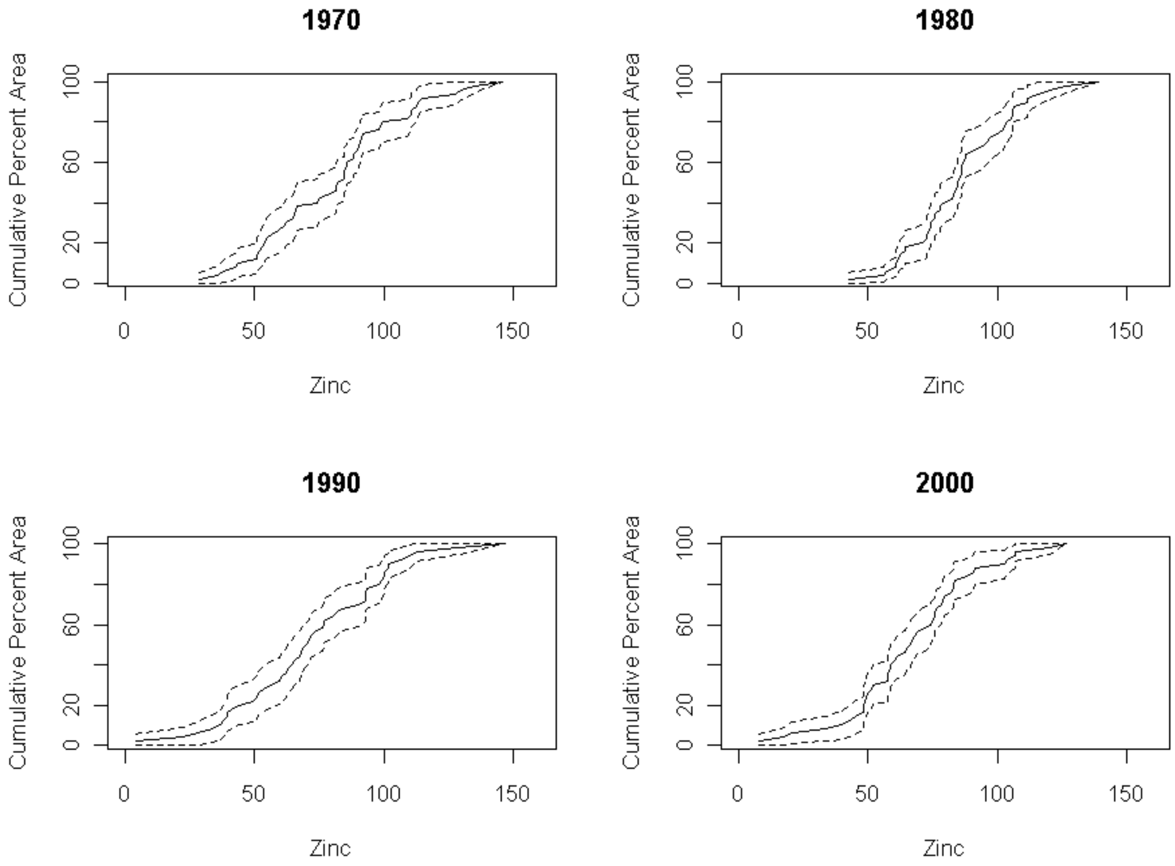

Figure 13. Cumulative percent of study area and 95% confidence intervals of Beaufort Sea coastal zone vs. zinc (ug g^{-1}).

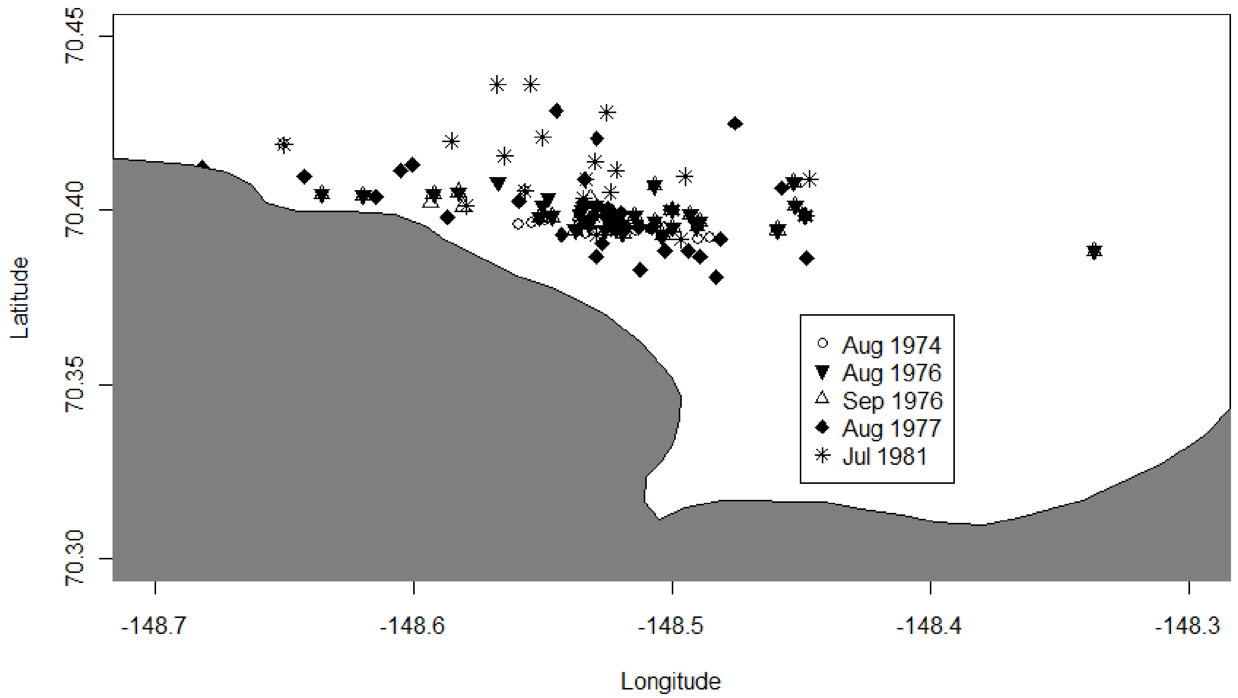

Figure 14. Macrofaunal sampling locations in Prudhoe Bay, Alaska, 1974-1981.

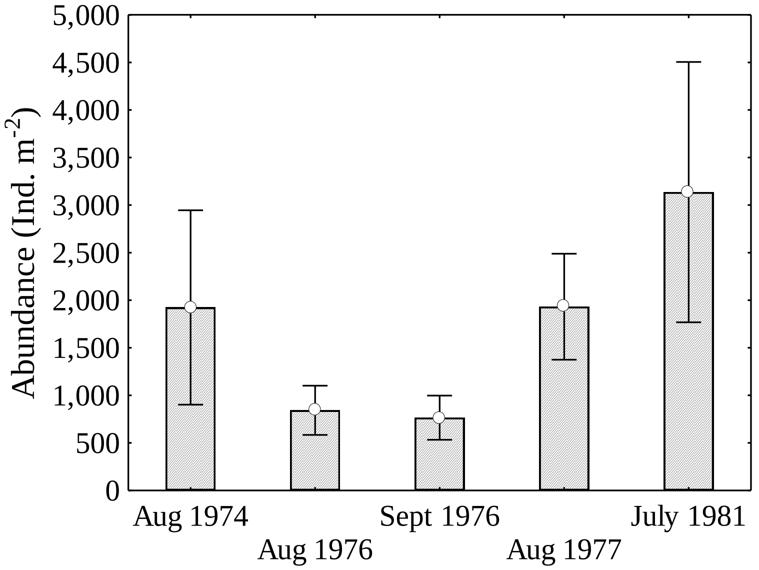

Figure 15. Whisker plots of average abundance by year. ANOVA comparisons of ln-transformed data indicated that Aug and September of 1976 were significantly lower than the other sampling periods, $P < 0.0001$.