

ABSTRACT

Title of Thesis: **DRIVERS OF EPIBENTHIC BIODIVERSITY
AND ABUNDANCE IN BARROW CANYON,
CHUKCHI SEA UTILIZING DROP CAMERA
VIDEO DATA**

Andrea R. Pfaff, Master of Science, 2022

Thesis Directed By: **Dr. Jacqueline M. Grebmeier
Marine-Estuarine and Environmental Science**

In the Northeastern Chukchi Sea's Barrow Canyon, modeling indicates that converging currents rapidly downwell high volumes of labile carbon creating a benthic biological hotspot. Utilizing a Drop Camera Video System, this thesis analyzes the epibenthic population across upper Barrow Canyon along the Distributed Biological Observatory transect DBO5. Results show that overall abundance of epibenthic fauna is highly correlated with depth while diversity is correlated with water mass variables such as bottom water temperature, salinity, nutrient concentrations, current speeds, and sediment grain size. Higher taxonomic diversity is found along the inshore slope of Barrow Canyon and correlated with conditions associated with the swifter inshore Alaskan Coastal Water. Taken together these data show that while particulate food and associated epibenthic abundance is highest in the Canyon's trough, there is a zonation of organisms between the inshore and offshore slope with the inshore slope supporting a higher diversity and predominantly suspension feeding organisms.

DRIVERS OF EPIBENTHIC BIODIVERSITY AND ABUNDANCE IN BARROW CANYON,
CHUKCHI SEA UTILIZING DROP CAMERA VIDEO DATA

Andrea R. Pfaff

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
Of the requirements for the degree of
Master of Science
2022

Advisory Committee:

Professor Jacqueline M. Grebmeier, UMCES CBL, Chair

Professor Lee W. Cooper, UMCES CBL

Associate Research Professor, Vyacheslav Lyubchich, UMCES CBL

© Copyright by
Andrea R. Pfaff
2022

Acknowledgments

First, I would like to thank my Primary Advisor and mentor Dr. Jaqueline Grebmeier for all her help, encouragement, patience, and support over the past two and a half years as I learned so much about the Pacific Arctic and work towards this thesis and degree. I would also like to extend a huge thank you to Dr. Lee Cooper who trained me in the Drop Camera Video System and allowed me to take such a front seat role in setting up and deploying the system during the two CCGS *Sir Wilfrid Laurier* cruises I was honored to take part in. Together, Drs. Grebmeier and Cooper have continually gone above and beyond in involving me in their research, answering my questions and helping me work towards my larger goals both in academically and professionally. Of course, I also want to thank Dr. Vyacheslav Lyubchich for always being available with help and input for statistical questions. All three of my committee members were integral in bringing this thesis to where it is today.

Lab members of the Grebmeier-Cooper lab have also been indispensable in supporting my research. Thank you to Dr. Christina Goethel for answering so many of my questions about both subject material and navigating administrative quirks. Her advice and friendship on land and at sea made pursuing my masters a joy. A big thank you also goes to Stephanie Soques and Alicia Clarke for training me in Arctic benthic infauna and epifauna identification. Along with the other members of the sorting lab, they also cataloged infauna via the grab samples which informed some of the basis for my work with the videotaped epifauna.

Additionally, I would like to thank members of other institutions who have provided data and expert input to this work. Thank you to Drs. Robert Pickart and Peigen Lin whose work and data on the absolute geostrophic velocity of the flow in Barrow Canyon was extremely important in fleshing out the dynamics between epibenthic abundance/diversity and environmental

conditions present in the Canyon. A big thank you also goes to the 2021 and 2022 crews of the CCGS Sir Wilfrid Laurier who aided in data collection in the field making this research possible.

I also want to take the opportunity to say a huge thank you to my family without whom I would not be where I am today. First, a thank you to my parents who have supported me emotionally and financially through every stage of my academic career, always being invested in my work and my goals. Next, I must thank my two older sisters, Sarah and Jennifer who helped pave the way through different academic trajectories and always provided practical advice as I navigated through similar situations. And finally, a wholehearted thank you to my wonderful fiancée Philip Brown who has done so much to encourage me towards my aims, remind me of the most important things in life and always agreed to proofread no matter what the subject matter, how long the document or how busy he was.

Financial support for this thesis was provided by PIs Grebmeier and Cooper from the Chesapeake Biological Laboratory through National Science Foundation grant #OPP-1917469.

| | |
|--|-------------|
| Title Page | |
| Copyright | |
| Acknowledgments | ii |
| Table of Contents | iv |
| List of Tables | vii |
| Chapter 1 | vii |
| Chapter 2 | vii |
| Chapter 3 | vii |
| List of Figures | viii |
| Chapter 1 | viii |
| Chapter 2 | viii |
| Appendix 1 | ix |
| Chapter 3 | ix |
| Appendix 2 | x |
| List of Abbreviations | xi |
| | |
| Chapter 1: Introduction | 1 |
| Potential Impacts to Benthic Diversity in a Changing Arctic..... | 1 |
| An Overview of Pacific Arctic Currents..... | 2 |
| Ocean Currents Impacts on Physical and Chemical Drivers in Barrow Canyon..... | 5 |
| Documented Biological Change in the Pacific Arctic | 7 |
| Description of Study Area | 11 |
| Rationale for Study | 13 |
| Hypothesis and Thesis Structure..... | 14 |
| References | 18 |
| Tables..... | 24 |
| Figures..... | 25 |
| | |
| Chapter 2: Integrating Drop Camera Video Data into the Distributed Biological Observatory Sampling Effort | 29 |
| 1. Introduction..... | 29 |
| 1.1 The Need for Robust Sampling in a Changing Pacific Arctic | 29 |
| 1.2 The Drop Camera Video System Sampling Technique..... | 30 |
| 1.3 Objective of Study | 31 |
| 1.4 Statement of Objectives, Justification, and Hypotheses | 32 |
| 2. Materials and Methods..... | 33 |
| 2.1 Image Processing and Data Collection | 33 |
| 2.2 Statistical Analysis | 35 |
| 3. Results..... | 36 |
| 3.1 Target Organisms..... | 36 |
| 3.2 Abundance of Organism groups and Taxonomic classes | 36 |
| 3.3 Abundance of Feeding Types | 37 |
| 3.4 Statistical Analysis of Organismal Abundance..... | 38 |
| 4. Discussion | 39 |

| | |
|--|------------|
| 4.1 Overview..... | 39 |
| 4.2 Standardization of Video Data Collections..... | 40 |
| 4.3 Procedural Example and Representative Results..... | 41 |
| Conclusions | 44 |
| References | 46 |
| Tables..... | 48 |
| Figures..... | 55 |
| Appendix 1 | 61 |
| | |
| Chapter 3: Drivers of Epibenthic Abundance and Diversity in the Barrow Canyon Region | 65 |
| 1. Introduction..... | 65 |
| 1.1 Understanding the importance of Abundance and Diversity in a changing Pacific Arctic..... | 65 |
| 1.2 Study Region and Drop Camera Video Sampling Technique | 66 |
| 1.3 Environmental Drivers in the Barrow Canon region | 68 |
| 1.4 Objective of Study | 69 |
| 1.5 Statement of Objectives, Justification, and Hypotheses | 69 |
| 2. Materials and Methods..... | 70 |
| 2.1 Data Collection | 70 |
| 2.2 Image Processing and Analysis | 71 |
| 2.3 Statistical Analysis | 72 |
| 3. Results..... | 73 |
| 3.1 Abundance, Feeding Groups and Diversity | 73 |
| 3.2 Changes in Diversity and Environmental Conditions over the Study Period | 75 |
| 3.3 Correlations between Epifaunal Abundance, Diversity, Feeding Groups and Environmental Conditions | 76 |
| 4. Discussion | 77 |
| 4.1 Overview..... | 77 |
| 4.2 Abundance Trends and Drivers and Outliers | 79 |
| 4.3 Feeding group Trends and Drivers | 82 |
| 4.4 Diversity Trends and Diversity | 83 |
| Conclusions and Future Work | 84 |
| References | 87 |
| Tables..... | 91 |
| Figures..... | 95 |
| Appendix 2 | 104 |
| | |
| Chapter 4: Conclusions | 106 |
| The Role of Drop Camera Video Data in Assessing Abundance and Diversity of Epibenthic Species in Today’s Arctic Research | 106 |
| Review of Project Goals and Key Findings | 108 |
| Future Work..... | 111 |
| References | 113 |

Master Reference List116

List of Tables

Chapter 1

Tables 1.1 Latitude, longitude and average approximate depth for the ten stations samples at DBO5

Chapter 2

Table 2.1 Overview of target organisms which can be identified with reasonable accuracy in the drop camera video data. Organisms are broken into four classifications of feeding types including **suspension**, **deposit**, organisms that can engage in **both** suspension and deposit feeding, and organisms that engage in **other** feeding types such as scavengers.

Table 2.2 The average abundance (individuals/m² or ind/m²) at BarC1-BarC10 for the three study years 2017, 2019 and 2021. Average total abundance (ind/m²) is calculated.

Table 2.3 Summary table of the preliminary statistical analysis performed on the faunal abundance (ind/m²) data collected from the drop camera videos. Shown are significance level values and subsequent statistical results for twelve analysis of variance tests and two normality tests. Highlighted tests are ones shown to have statically significant results.

Chapter 3

Table 3.1 Shannon-Weaver Diversity Indices for 2017, 2019 and 2021 at each of the ten DBO5 Barrow Canyon (BarC) stations (BarC1-BarC10). Minimum values are indicated with ⁺ and maximum values are marked with *.

Table 3.2 Table 3.2 Results of one-way ANOVA F-test for the differences in environmental variables across the study period along the DBO5 transect. The p-values are highlighted as follows: significant (p-value < .05), highly significant (p-value ≤ .001).

Table 3.3 Spearman's rank correlation coefficients in larger font on top and p-values with smaller font on bottom for the 70 tested correlations between overall station abundance, diversity, abundance of feeding groups (suspension, deposit and organisms that can engage in both) and 14 environmental variables. The p-values are adjusted with the Benjamini & Hochberg method and indicated with highlighting and notation as follows: significant (p-value < .05), highly significant (p-value ≤ .001).

Table 3.4 Spearman's rank correlation test results (coefficients in bold on top and p-values italicized below) between the abundance of the sea cucumber Order Elasipodida (*O. glacialis*) during 2017, 2019 and 2021 and eight environment variables including bottom water temperature, salinity, nutrients, and chlorophyll a (chl a). Surface sediment chlorophyll a (chl) a was also determined. Also included are the p-values for the One-way ANOVAs performed on the eight environmental variables to show if any of the variables correlated to Elasipodida abundance also vary significantly between 2017, 2019 and 2021.

List of Figures

Chapter 1

Figure 1.1 A Map of the various branches of prevailing currents in the Pacific Arctic as well as features of importance across the Sub-Arctic and Pacific Arctic regions (Adapted from Stabeno et al. 2018).

Figure 1.2 A map of the eight sampling regions that make up the Distributed Biological Observatory (DBO) extending from the northern Bering Sea, through the Chukchi Sea and into the Beaufort Sea. Each red bounding box represents a ‘hotspot’ of biological productivity and biodiversity while the red points are sampling transects within each DBO region. Maximum and minimum median ice extent based on Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMIS) satellite-derived sea-ice concentrations (1980–2018) are also shown on this figure (Figure from Grebmeier et al. 2019).

Figure 1.3 A map of the ten stations that make up the DBO5 sampling transect made with Google Earth Engine and related datasets. The bathymetry of the region is visualized with the color bar which denotes to scale from 200m depth to surface (Amante & Eakins, 2009). The ten stations (BarC1-BarC10) are denoted by the black dots and labeled.

Figure 1.4 A map of elapsed time in days for simulated point source tracers to reach the DBO5 transect from the Chukchi shelf. The blue contours show days elapsed while the red hatching denotes the period of 7–21 days, corresponding to the most pertinent source region of Chlorophyll-a to the pycnocline in Barrow Canyon (Figure from Pickart et al., 2019).

Chapter 2

Figure 2.1 A map of the Distributed Biological Observatory 5 (DBO5) and surrounding region in the Northeastern Chukchi Sea which shows the location and dominant taxa of the ten stations that make up the cross-canyon sampling transect (BarC1- BarC10). Dominant taxa are based on abundance determined from the CCGS Sir Wilfrid Laurier July cruises in 2017, 2019 and 2021. Additional information of station depths and the regions bathymetry can be found in Table 1.1 and Figure 1.3, respectively. More information on the dominant taxa and references can be found in Table 2.1. Figure prepared using Google Earth Engine (<https://code.earthengine.google.com/>)

Figure 2.2 Examples of still image data exported from videos collected on the CCGS Sir Wilfrid Laurier July 2021 cruise. Each image is from the following respective stations: a) BarC2, b) BarC3, c) BarC4, d) BarC6, e) BarC4, f) BarC10. Note BarC=Barrow Canyon.

Figure 2.3 A bar graph showing the logarithmic relative abundance (ind/m²) of organisms across the DBO5 sampling stations (BarC1-BarC10). The x-axis indicates the station progression from west (BarC10) to east (BarC1) moving left to right across the axis.

Figure 2.4 A bar graph showing the average proportion of abundance (ind/m²) across the DBO5 sampling stations (BarC1-BarC10). The x-axis shows the station progression from west (BarC10) to east (BarC1) moving left to right across the axis.

Figure 2.5 A bar graph showing the average proportion of individual faunal feeding type per m² across the DBO5 sampling stations (BarC1-BarC10). The x-axis shows the station progression from West (BarC10) to East (BarC1) moving left to right across the axis. Feeding types include deposit feeders, suspension feeders and organisms that can engage in both suspension or deposit feeding depending on environmental conditions.

Figure 2.6 A still photo from BarC3 taken from the Canadian Coast Guard Vessel Sir Wilfrid Laurier 2022 video footage that shows extended tentacles on the sea cucumber *O. glacialis* circled in white. The tip of each tentacle contains papillae that secrete an adhesive material to capture particulate detritus to allow *O. glacialis* to suspension feed (Madsen & Hansen, 1994).

Appendix 1

Figure A1.1 A diagram of the Drop Camera Video System which details the major components of the system including the lasers, lights, thermometer, pressure transducer for depth measurements and camera. This diagram also shows how power is supplied to the unit through an electronic load bearing cable and split power cables that supply different components individually.

Figure A1.2 Images detailing the setup and deployment of the Drop Camera Video System aboard the CCGS Sir Wilfrid Laurier. A) is the view looking at both the indoor bay where the camera is operated from and the deck deployment area. B) shows camera system deployment using a snatch block fixed pulley system. C) is an image of the indoor bay where the camera is operated from on the desktop monitor, stored between stations and the electronic load bearing cable reel. D) shows the deployment setup including the snatch block fixed pulley system and the dark box for the live view laptop on deck.

Chapter 3

Figure 3.1 Temperature, salinity and velocity gradients observed across the DBO5 line with BarC1 located on the right side of each figure, BarC5 at 30 km distance and BarC10 located on the left side of the figure. These figures show mean values derived from 28 Non-upwelling occupations and 17 Upwelling occupations and were made using MATLAB which is a programming language and numeric computing environment developed by MathWorks (<https://www.mathworks.com/>). Figures and data courtesy of Dr. Robert Pickart of Woods Hole Oceanographic Institution.

Figure 3.2 A map of the ten stations that make up the DBO5 sampling transect. Also displayed is the bathymetry of the Barrow Canyon region and percentage of sediment particles that are equal to or over a given threshold of fineness (5 phi on the Krumbein phi scale) These variables are shown via two different color bar scales which are denoted on the map. The base map was prepared using Google Earth Engine, the bathymetry data is sourced from the Google Earth Engine data set Amante & Eakins, 2009, and the grain-size data is an average value collected on the CCGS Sir Wilfrid Laurier occupations of the DBO5 line during 2017, 2019 and 2021. The ten stations (BarC1-BarC10) are denoted by the black dots and labeled. This figure shows that the inshore slope of Barrow Canyon (BarC1-BarC5) is predominately characterized by lower percentages of finer sediments (i. e. coarser sediments) while the offshore slope of Barrow Canyon (BarC6-BarC10) contains higher percentages of finer sediments.

Figure 3.3 a) The DBO5 transect with an overlaid schematic of the flow of the two primary water masses present in Barrow Canyon: the inshore Alaskan Coastal Water and offshore Bering Sea Water. Adapted from (Pickart et al., 2021), b) a vertical transect of the inshore slope of Barrow Canyon with an idealized version of the vertical advection cell caused by current interactions that advect food sources directly to the trough of the Canyon. Sourced from (Pickart et al., 2021), c) a vertical transect of fluorescence (mg m^{-3}) along the DBO5 transect with station position denoted along the top of the figure. This figure shows data which supports the idealized vertical advection cell shown in figure 3.3b. Sourced from Pickart et al. 2021, and d) Chl a concentration based on the MODIS image for June 10, 2017. The red outlined region corresponds with the DBO5 source region which can be seen in Figure 1.4. Sourced from (Pickart et al., 2021).

Figure 3.4 Shannon-Weaver Diversity Indices at DBO5 during 2017, 2019 and 2021. Minimum Indices are observed all three years at BarC8 while maximum Indices are observed all three years at BarC1. Specific values are referenced in Table 3.1. The plot was prepared using Microsoft Excel.

Figure 3.5 Mean total abundance and diversity from the study years at each station along the DBO5 transect. Abundance is measured in individuals per meter² (ind/m^2) and graphed in green with values logarithmically displayed on the left y-axis. The Shannon-Weaver Diversity Indices are graphed in orange with values shown on the right y-axis. Abundance peaks near the trough of the Canyon at BarC6 and generally decrease bidirectionally while diversity reaches a minimum at BarC8 and increases bidirectionally. Plot was made with Microsoft Excel.

Figure 3.6 Abundance and diversity at the 10 stations that make up the DBO5 transect (BarC1-BarC10) overlaid on bathymetry of the region. Abundance is shown as the size of the pie symbol scaled logarithmically for ease of visualization and the 15 groupings of organism counted are each displayed by a different color in the pie chart. The base map was prepared using Google Earth Engine and bathymetry data sourced from the Google Earth Engine data set (Amante & Eakins, 2009).

Figure 3.7 Distribution of monthly infauna biomass across the DBO5 line using data from 1999 to 2015 overlaid upon a bathymetry curve (grey). The ten sampling stations are marked along the upper x axis. The bathymetry is from the USGCS Healy echosounder. See Grebmeier and Cooper (2020) for methods and cruise information. Sourced from Pickart et al. (2021).

Figure 3.8 Abundance of Elsipodida (*O. glacialis*) from 2007 to 2022 utilizing available years of data from benthic infauna Van Veen grabs and epibenthic Drop Camera Video System (DCVS) data. Note: abundance is graphed logarithmically.

Figure 3.9 Example images of organisms clustering on rock formations as well as example of more random distribution of organisms across the benthos at the same stations. Images a), b), e), and f) are taken from 2021 data at BarC1 while images c), d), g), and h) are taken from 2021 data at BarC2.

Appendix 2

Figure A2.1 Information on sampling instruments, related data and collection years used as a part of this study.

List of Abbreviations

| | |
|----------|---|
| ACC | Alaskan Coastal Current |
| ACW | Alaskan Coastal Water |
| ADCP | Acoustic Doppler Current Profiler |
| ANOVA | Analysis of Variance |
| AW | Anadyr Water |
| BarC | Barrow Canyon sampling stations (1-10) |
| BSAW | Bering Shelf and Anadyr Water |
| BSW | Bering Sea Water |
| BW | Bottom Water |
| CCGS SWL | Canadian Coast Guard Ship the Sir Wilfrid Laurier |
| CTD | Conductivity, Temperature and Depth Sensor |
| DBO | Distributed Biological Observatory |
| DBO5 | Distributed Biological Observatory Transect 5 |
| DCVS | Drop Camera Video System |
| PAR | Pacific Arctic Region |
| SWDI | Shannon Weaver Diversity Indices |

Chapter 1: Introduction

Potential Impacts to Benthic Diversity in a Changing Arctic

According to Box et al. (2019), a substantial shift in the Arctic Ocean's physical regime occurred in 1971 which was followed by decades of continuously changing conditions (Box et al., 2019). Most notable among these changes are a dramatic decrease in both thickness and extent of seasonal sea ice, an earlier retreat and later return of sea ice, rising surface seawater temperatures, and an intensification of the hydrological cycle through increased humidity, precipitation, and river discharge (Box et al., 2019; Peterson et al., 2002, 2006; Wood et al., 2015). Connected with these observations are changing velocities of Arctic currents that play a vital role in regulating the other aspects of the region's chemistry and biology. Changes in the magnitude and direction of currents impact the salinity, temperature, sediment composition and the strength of benthic-pelagic coupling (Danielson et al., 2020; Dunton et al., 2005; Grebmeier, 2012; Woodgate & Peralta-Ferriz, 2021). Shifting environmental variables have already resulted in documented changes in the distribution, biomass, and abundance of many Arctic organisms (Grebmeier, 2012; Grebmeier et al., 2010; Hauser et al., 2018). These changes can be exacerbated in certain areas due to shallower depths and convergences of major flows which enable currents to play a larger role in regulating the chemical and physical makeup of the benthos and the resulting biological regime (Pickart et al., 2021).

Barrow Canyon is a distinct physical feature that begins on the Chukchi shelf at 50m depth and descends to the Canada Basin of the Arctic Ocean at a depth of 3,800m (Figure 1.1). At the southern end of the Canyon on the Chukchi Sea shelf, water depths of ~50m are shallow enough to allow surface currents to directly affect the benthos. In addition, because

it is one of three major northern outlets leading from the Pacific Ocean influenced Arctic shelves, several important shelf currents converge in the Barrow Canyon region including the Alaskan Coastal Current (ACC) near Alaska and Bering Shelf and Anadyr Water (BSAW) which circulates offshore around Hanna Shoal (Danielson et al., 2012; Garrison & Becker, 1976; Mountain et al., 1976; Stabeno et al., 2018; Weingartner et al., 1998, 2005). Therefore, Barrow Canyon is a prime example of a region where changes in the prevailing currents could have cascading effects on benthic biology. However, little is known about how currents and other environmental drivers in the region presently affect the diversity and abundance of benthic species in relation to how changes in those variables may impact the robust diversity that currently marks the Canyon region (Iken et al., 2019; Mueter et al., 2021).

This study aims to provide a greater understanding of the role of currents and other environmental drivers in determining both the abundance and diversity over time of epibenthic species in Barrow Canyon by standardizing data processing techniques for analyzing benthic video data collected in the region (e.g. Cooper et al., 2019) as well as correlating time series of abundance and diversity measurements from the video data with other environmental measurements collected via shipboard Acoustic Doppler Current Profilers (ADCP), Van Veen sediments grab samples and Conductivity-Temperature-Depth (CTD) casts. This approach allows for more informed modeling of benthic biology, which will lead to a more accurate understanding of the role of currents in shaping the physical, chemical, and ultimately biological composition of this region.

An Overview of Pacific Arctic Currents

The two seas relevant to my study include the Bering Sea in the south and the Chukchi Sea in the north in the Pacific Arctic. The benthos of the Northern Bering Sea and the Chukchi

Sea are located on broad continental shelves with average depths of 50m, connected through the Bering Strait. The northern edge of the Chukchi Sea is bounded by a shelf break located 800km northward from Bering Strait along the Arctic Ocean's Canada Basin (Figure 1.1). The Pacific water entering the Chukchi Sea through Bering Strait flows predominantly northward, although it can be modified by local winds and bathymetry (Stabeno et al., 2018; Woodgate, 2018) (Figure 1.1). This makes the Northern Bering and Chukchi Seas a crucial inflow region for the Arctic Ocean (Carmack & Wassmann, 2006). This flow consists of three water mass types: Alaskan Coastal Water carried in the Alaskan Coastal Current (ACC), and the offshore Anadyr Water (AW) and Bering Sea Water (BSW) (Coachman et al., 1975; Danielson et al., 2017, 2020; Gong & Pickart, 2015; Stabeno et al., 2018; Woodgate et al., 2005). The ACC (in summer) is warm, fresh, nutrient-poor and it is only present seasonally while the AW has colder temperatures, higher salinity content, nutrient-rich, and has year-round consistency (Hennon et al., 2022). The BSW is also present year-round and is situated between the ACC and AW both geographically and on salinity and temperature gradients (Stabeno et al., 2016). The combination of these water masses regulates the heat, salinity content, nutrients, and particulate food in the Chukchi Sea.

Following the bathymetry of the region, a generally northward flow in the Chukchi Sea travels via the offshore Central Channel and nearshore Alaskan Coastal Current that joins with a northeasterly flow south of Hanna Shoal to merge at Barrow Canyon where the water masses converge and exit the shelf (Stabeno et al., 2018) (Figure 1.1). This flow in Barrow Canyon extends to depth in the upper portion of the Canyon directly impacting the benthos at 300m and above with the strongest impact occurring during spring and summer advection (Stabeno et al., 2018). Once exiting the shelf via Barrow Canyon, about 70% of the converged

flow turns westward to create the Chukchi Slope Current which runs parallel to the Beaufort Gyre (Pickart et al., 2021). The Beaufort Gyre is a major anticyclonic sea ice circulation feature of the Arctic Ocean that regulates inflow and outflow in the Pacific side of the Arctic Ocean (Armitage et al., 2020; Stabeno et al., 2018).

It is widely recognized that warming seas and melting sea ice are impacting the world's ocean circulation and the Arctic Ocean is a focal point for many of these changes (Armitage et al., 2020; Timmermans & Marshall, 2020). However, accurately identifying and predicting these changes requires complicated methodological practices with significant uncertainty. The velocity of the Beaufort Gyre has and is predicted to continue increasing in magnitude due to the enhanced mechanical energy input from loss of sea ice and acceleration of inflows of Pacific Arctic waters (Armitage et al., 2020). This increasingly energetic gyre, in conjunction with mesoscale eddies, causes an intensification of freshwater retention in the region; the strength of the gyre decreases output while river discharge and precipitation increase input (Armitage et al., 2020; Box et al., 2019). This is resulting in an overall decrease in the salinity of the surface Arctic Ocean and a build-up over time of stored fresh water in the gyre.

In the Chukchi Sea, uncertainties persist relative to the present and predicted changes in prevailing currents as temperatures rise and seasonal sea ice decreases. The on-going increase in Pacific flow northward contributes to a stronger, faster Beaufort Gyre, but it is not known if this flow is necessarily going to continue to increase (Armitage et al., 2020). In addition, the increased mechanical energy input due to melting sea ice does not currently correspond to increases in potential energy storage in the Beaufort Sea because of mesoscale eddies which dissipate the energy and help keep the system stable (Armitage et al., 2020).

However, this could cause a positive feedback loop in which the increased ice melt due to the advection from the mesoscale eddies will overwhelm the energy dissipation ability of the eddies and ultimately destabilize the system (Armitage et al., 2020). In-conjunction with possible changes in wind direction, system destabilization would result in the Beaufort Gyre releasing high levels of freshwater that it currently retains (Armitage et al., 2020). This will cause a substantial and far-reaching shift in the present structure and dynamics of the Arctic Ocean and its surrounding inflow and outflow (Armitage et al., 2020; Box et al., 2019; Timmermans & Marshall, 2020). In this scenario, the effect of changes will be witnessed most in the dominant water flux areas between regions separated by the boundary shelf current, because they will act as a buffer point between two potentially very different current restructurings. Therefore, Barrow Canyon, as one of these important boundary regions between the Pacific Arctic shelf and the Canada Basin, will likely undergo changes in its physical regime in the coming decades. It is unclear how these changes will unfold in Barrow Canyon, but it is likely that the changes will be variable, unpredictable, and marked by wider extremes (Wood et al., 2015).

Ocean Currents Impacts on Physical and Chemical Drivers in Barrow Canyon

Ocean currents act as regulators of numerous physical and chemical features of marine ecosystems. Their primary role is that of transport as they transfer heat, salinity, organic and inorganic nutrients as well as particulate food from one region to the next. In the context of Barrow Canyon, the ACC brings warmer water and lower salinity to the inshore slope of Barrow Canyon during the summer while the BSAW bring colder temperatures and higher salinity to the offshore slope of Barrow Canyon (Pickart et al., 2021; Stabeno et al., 2018). The BSAW also carries the primary input of chlorophyll a (hereafter chl a) to the region by

transporting highly productive waters across the Chukchi Sea northward through the Central Channel, clockwise around Hanna Shoal, and northeastward into Barrow Canyon (Figure 1.1) (Pickart et al., 2021). The velocity of the current through the Central Channel dictates the timescales by which surface produced chlorophyll biomass is transported to the Barrow Canyon region with the current average being ≈ 90 days from Bering Strait to Barrow Canyon during the ice-free season (Stabeno et al., 2018). Upon reaching Barrow Canyon, the interaction between the BSAW and ACC creates a vertical circulation cell near the center of the Canyon which forcefully transports chl a biomass, nutrients and oxygen to the Canyon's benthos (Pickart et al., 2021). This direct transport to the benthos creates a benthic biological hotspot characterized by relatively high biomass, abundance, and diversity in comparison with surrounding regions. Therefore, even minor changes in the velocity of either the BSAW or ACC could impact the temperature and salinity gradient from the inshore to offshore slope of Barrow Canyon as well as the horizontal and vertical transport of nutrients and food which would ultimately affect the benthic biological hotspot in the Canyon.

In addition to transport on regional scales, currents can locally affect the benthos through deposit or resuspension of particulate food as well as impact sediment composition. Localized benthic flow can be described on the scale from turbulent to laminar; turbulent flow is irregular and chaotic while laminar flow, which is an ideal concept not observed in nature, is smooth and streamlined (Reynolds, 1883). Variations in flows are created by the interaction between the velocity of benthic currents, bathymetry, pressure, and the composition of the benthos. Areas with higher turbulence generally have higher current velocities, suspended/resuspended particulate matter, and coarser sediment grain size while areas with lower turbulence typically have lower current velocities, deposited particulate matter and

finer, muddier sediments (Krumbein, 1934). Sediment structure and the positioning of particulate matter directly impact the biological composition of local benthic environments (e.g. suspension feeders are typically found in more turbulent flow while deposit feeders are typically found in more laminar flow) (Sebens et al., 2017). Therefore, by shaping the physical and chemical environments on regional and local scales, currents can dictate both abundance and diversity of benthic organisms.

Documented Biological Change in the Pacific Arctic

Coincident with the documented changes in the physical and chemical regimes across the Pacific Arctic ecosystem are contemporaneous shifts in the biological domain (Frey et al., 2021; Goethel et al., 2019; Grebmeier, 2012; Grebmeier et al., 2010, 2018; Mueter et al., 2021). The base of the Arctic food web consists of autotrophic single-celled algae which reside in both the water column as phytoplankton and in the sea ice as ice algae. There are also locally macroalgae communities such as kelps that contribute to the nearshore primary production pool in the Arctic (Filbee-Dexter et al., 2019). Both micro- and macroalgae productivity are light and nutrient dependent, meaning that primary production in the Arctic is highly seasonal with respect to available light and nutrient parameters (Frey et al., 2021). Therefore, the timing, location, and magnitude of maximum primary production is a result of the relationship between nutrient availability in and near the sea ice, water mass nutrients, and light availability. Rapid changes in sea ice melt can directly impact many aspects of primary production in the Arctic although the core source of nutrients in the study region are from the Pacific waters entering the Arctic as well as benthic carbon cycling on the shallow shelves (Frey et al., 2021). These shifting patterns have already been established by numerous studies that show higher primary production in 2021 relative to the 2003-20 mean across most

of the Arctic (Frey et al., 2021) as well a shift in the type of phytoplankton bloom in the Chukchi Sea from under-ice blooms to marginal ice edge blooms (Waga et al., 2021). On the other hand, Cooper and Grebmeier (2022) showed that changes in primary production are not consistent across all areas; no overall trends were observed in chlorophyll biomass in July in any of the Distributed Biological Observatory stations, including within Barrow Canyon over periods as long as 20 years since 2000 (Cooper & Grebmeier, 2022). However, the decrease in multiyear ice and the extent of seasonal sea ice certainly threatens extirpation of cryophilic flora even if no overall trends have been observed (Nelson et al., 2014). In addition to these changes, water temperatures can shift the makeup and distribution of primary producers, including shifts in water column diatom populations that are the major producers of organic carbon in the region (Hill et al., 2013; Nelson et al., 2014). A less predominant example of the effects of rising water temperatures is that of kelp. Non-polar boreal kelp species are predicted to continue expanding their range into the Arctic while endemic Arctic species will become increasingly limited in their distribution (Goldsmit et al., 2021). These indications are consistent with significant disturbances in the base of the Arctic food web that may shift and potentially destabilize upper trophic levels.

The benthic ecosystem is critically linked to primary production in the Pacific Arctic because of the strong benthic-pelagic coupling in the region (Grebmeier et al., 2010; Grebmeier & McRoy, 1989). This tight benthic-pelagic coupling is the result of shallow depths as well as strong vertical transport in certain areas like Barrow Canyon (Cooper et al., 2005; Pickart et al., 2021). The distribution of particulate food matter, which is dictated by benthic-pelagic coupling has been shown to be a key environmental driver of benthic abundance, biomass and metabolic rates in the Pacific Arctic (Goethel et al., 2019; Grebmeier

& McRoy, 1989). For example, while higher temperatures usually lead to higher benthic metabolism, the warmer ACC is limited in its support of benthic metabolism compared to the colder BSAW because of the variability in water column primary production between the two water masses (Grebmeier & McRoy, 1989). Therefore, the general trends of benthic biomass can be closely linked to variation in primary productivity.

The northward repositioning of the maximum seasonal sea ice extent has been linked to notable shifts in species composition with a general northward expansion of benthic faunal range (Goethel et al., 2019; Grebmeier, 2012; Grebmeier et al., 2010). Along with this expansion is a northward shift in high benthic biomass and reorganization of macrofaunal composition with new dominant species emerging in some areas (Grebmeier et al., 2018). Time-series analysis of these changes suggests that there is a statistically significant transition occurring in the benthic habitat in the northern Bering Sea and that the region has potentially reached a critical “tipping point”; this would cause the system to transition from benthic dominated to pelagic dominated (Grebmeier et al., 2018). This shift away from benthically supported higher trophic levels could lead to ecosystem wide ramifications on the structure and potentially productivity of the Pacific Arctic.

The highest trophic levels in the Pacific Arctic can be affected by sea ice reduction and warming temperatures, both directly through changes in habitat and migration or indirectly through the food web (Grebmeier et al., 2010; Hauser et al., 2018). An example of a higher trophic organism directly impacted by the decrease in the thickness and extent of seasonal sea ice is the Pacific walrus (*Odobenus rosmarus divergens*), which is an ice dependent Arctic marine mammal. For the walrus, sea ice decrease causes a loss of habitat and reduction of foraging grounds as they typically haul out on land as sea ice declines

seasonally, thus forcing them to either use nearshore, less productive benthic habitat or extending at sea time and energy expenditure to reach offshore rich benthic regions (Bluhm & Gradinger, 2008; Grebmeier et al., 2010; Jay et al., 2012). While similar impacts to habitat are occurring to other upper trophic marine species, the indirect effects of the changing environment through the reordering of the food web, pose more threatening changes to those same species (Moore et al., 2014). For benthivorous seabirds and marine mammals, changes in the benthic population and the potential shift to a pelagic dominated system pose a significant threat to their food sources (Grebmeier et al., 2010). The general northward expansion of benthic faunal range in tandem with shifts in dominant benthic macrofauna and decreases in biomass of key species influence whether predators will have sufficient prey in appropriate locations to support their current populations. For example, a species of clam (*Macoma calcaria*) that is a major source of prey for Pacific walruses has been shown to have significant population shifts with both increases and decreases in certain regions of the northern Bering and Chukchi Seas (Goethel et al., 2019). This will likely have cascading effects such as shifting foraging areas and the potential for increased competition between walruses and other predators who rely on *M. calcaria* populations, such as several species of sea stars and the spectacled eider (*Somateria fischeri*), which is a diving sea duck that is classified as threatened under the US Endangered Species Act. Therefore, the documented and predicated changes in Pacific Arctic benthic populations resulting from decreasing sea ice, changing currents, and shifting food supply will likely have cascading consequences for a wide range of upper trophic organisms.

Shifts of Pacific Arctic biodiversity at all trophic levels is another result of changing environmental conditions. Biological abundance is not necessarily correlated to diversity and

studying both aspects of the biological system are necessary to understand health, stability, and future impacts of the changing environment (Box et al., 2019; Grebmeier, 2012; Grebmeier et al., 2010; Hauser et al., 2018; Lu et al., 2021; Wood et al., 2015). While abundance and biodiversity are important across all trophic levels, for this study I assess both variables in specifically epibenthic fauna across Barrow Canyon. A diverse assemblage of benthic species contributes to ecosystem health not only as a robust food source for higher trophic levels, but also by affecting the chemical properties and composition of sediments, through activities such as feeding and burrowing (Graf & Rosenberg, 1997; Lu et al., 2021; Snelgrove, 1998). Therefore, diversity of epibenthic species is both impacted by, and contributes to, changes in the benthic environment, which ultimately affects the environmental niches occupied by different species. In addition, environmental shifts cause destabilization of not only the environmental conditions but of abundance and biodiversity that can result in a positive feedback loop of benthic biological reorganization. The impacts of shifting conditions on both abundance and diversity varies between locations and it is complex to predict. Therefore, the uncertainty of changing environmental conditions influence on ecosystem health via biodiversity and abundance, warrants further study on local scales in the Northeastern Chukchi Sea.

Description of Study Area

As described above, Barrow Canyon is a major outlet from the Chukchi Sea shelf. The high flux of water through the descending benthos brings surface and water column primary production from the greater shelf region to the Canyon where it is transported offshore. Ten sampling stations that form a cross-canyon transect were identified in the early 2000's as a prime biodiversity hotspot for the region (Figure 1.2). These sampling stations

have since been incorporated into the fifth transect developed as part of the Distributed Biological Observatory (DBO), hereafter DBO5. The DBO is an internationally coordinated Pacific Arctic sampling effort aimed at providing long-term biological, chemical and physical sampling data that will help to assess changes in both the water column and benthic community composition and biomass as seasonal sea ice declines and other ecosystem changes emerge (Grebmeier et al., 2019). Stations in Barrow Canyon (BarC) are labelled on a nearshore (BarC1) to offshore (BarC10) transect over an upper portion of the Canyon in shallow waters approximately 60 nautical miles from the head of the Canyon as it enters the Canada Basin (Figure 1.3). The sampling stations descend in depth along the inshore stations BarC1-BarC5 and ascend in depth along the offshore stations BarC5-BarC10 (Table 1.1). At each station the following measurements were taken and used to inform the Results and Discussion sections in Chapter 3 of this thesis: Depth, Temperature, Salinity, Sediment Grain Size, Surface Sediment Chlorophyll-a, Bottom Water Chlorophyll-a, Velocity of Currents, Oxygen, Nutrient Concentration, Total Organic Carbon (TOC) of the surface sediments, Total Organic Nitrogen (TON) of the surface sediments, and abundance of target epibenthic organisms.

In addition to the specific sampling region, the surrounding regions have a strong impact on Barrow Canyon as they are the source of the Canyon's labile primary productivity (Pickart et al. 2019). Using simulated tracers, specific areas to the southwest of Barrow Canyon have been identified as the most important of these source regions (Figure 1.4). The greater source region is broken down by days elapsed transporting particulate matter from a specific area upstream of Barrow Canyon (Point A) to the base of Barrow Canyon (Point B) through the currents and vertical advection cell mentioned previously. The fewer days

required to transport particulate matter from Point A to Point B, the stronger that area's impact on food supply in Barrow Canyon. The area which corresponds to a transport time of 7 to 21 days has been established as the most pertinent zone at which to examine surface productivity as it relates to food supply in the Canyon region (Pickart et al., 2021).

Rationale for Study

As established above, the Arctic Ocean and surrounding regions, particularly the Pacific Arctic, are rapidly changing. To understand and catalog those changes requires broad sampling of physical, chemical, and biological aspects of the system which inform both coarse and fine scale assessments of dynamic shifts occurring at all levels throughout the region (Grebmeier et al., 2019). Barrow Canyon is a particularly interesting system because it is a major connection point between the Pacific Arctic shelves and the deeper Arctic Ocean and therefore warrants a specialized focus on its shifting physical, chemical, and biological regimes. There has been extensive research on the system's currents, nutrients, primary producers, fish and mammal populations (e.g. Moore et al., 2014; Mountain et al., 1976; Pickart et al., 2021; Rand et al., 2018; Stabeno et al., 2018) but information on the epibenthic population in the DBO5 region is still lacking due to sampling challenges which result from a rocky bottom in certain sections of the Canyon and the Canyon's depth. This means that while the epibenthic populations in Barrow Canyon have been explored, there has not been sufficient fine scale assessment to understand how both abundance and diversity varies within the Canyon rather than between the Canyon and the surrounding shelf region (Iken et al., 2019; Mueter et al., 2021; Rand et al., 2018). Understanding the benthic community in the Canyon is especially important as knowledge of the composition of benthic biological communities increases our understanding of how physical and chemical changes are

impacting primary productivity, and indirectly impact upper trophic organisms through the food web. The strength of this impact is particularly strong in the Pacific Arctic due to the tight benthic-pelagic coupling in the region (Grebmeier, 2012).

This study aims to expand upon previous research in the region by further exploring and standardizing a previously used sampling technique to analyze epibenthic populations across Barrow Canyon (Cooper et al., 2019). In this prior study, a drop camera video system was used to document the abundance of epi-benthic populations *in-situ*. Because the camera visually surveys the benthos rather than contacting the bottom, it can be used throughout the diverse sediment composition found across the Canyon. Therefore, by standardizing collection and analysis of this drop camera video data, there is potential to greatly increase our understanding of the epibenthic population and how it is changing in response to environmental drivers in the region. The epifauna previously observed in Barrow Canyon includes brittle stars, *Psolus* sea cucumbers, soft corals (sea raspberry), sea urchins, basket stars, *Opilio* crabs, fish, small pink sea cucumbers, sea anemones, king crabs, hermit crabs, solitary corals, *Boltenia* tunicates, hermit crab, and bryozoans (Cooper et al., 2019). This study will expand upon this list of organisms by quantifying not only names of organisms but their abundance, taxonomic diversity, and functional diversity through an analysis of feeding type distribution, using the approach of Rand et al. (2018). This will strengthen our understanding of what drivers affect abundance and distribution of epibenthic fauna and what environmental changes may result in shifts to the present biodiversity observed there.

Hypothesis and Thesis Structure

Two objectives and six questions were identified and are explored in the following two chapters; Chapter 2 objectives and questions outline benthic camera methods and observational findings and the questions of Chapter 3 address environmental drivers of benthic biodiversity in Barrow Canyon. The goal of these objectives and question is to improve the effectiveness of drop camera video data as an epibenthic sampling technique and to better understand the drivers of abundance and diversity of epibenthic species in the Barrow Canyon Region. The chapter 2 questions and objectives are listed below as 2.1-2.4 and chapter 3 questions as 3.1-3.4:

- 2.1 Establish standard operating procedures for the collection and analysis of drop camera video data in the Pacific Arctic region.
- 2.2 Determine which epibenthic organisms can be identified with reasonable accuracy and establish groupings of organisms based on taxonomy.
- 2.3 What is the abundance of these target organisms through the years of available data?
- 2.4 Are there statistically significant differences in the abundance of key species across the study period?
- 3.1 What is the average epibenthic diversity of organisms at each station across Barrow Canyon (BarC1-BarC10)?
- 3.2 How does epibenthic diversity relate to other environmental variables across the Canyon?
- 3.3 What are the most statistically significant drivers of epibenthic diversity in Barrow Canyon?

3.4 How could those drivers impact the future of the Canyon's epibenthic species composition?

To achieve these objectives, several activities and hypotheses are developed to test the effectiveness of drop camera video data in answering questions relating to the abundance and diversity of epibenthic species. The activities are evaluated, and hypotheses assessed in the subsequent two chapters utilizing several experiments and analysis techniques.

Chapter 2 accomplishes objectives 2.1, 2.2, 2.3 and 2.4 by outlining a standard operating procedure for imaging and analyzing video data as well as establishing groupings of organisms that can be accurately identified within the data. Utilizing these groupings, a procedural example is conducted along the DBO5 transect using video data collected during the July occupation of the line in 2017, 2019 and 2021 aboard the CCGS Sir Wilfrid Laurier. Using the abundance data collected via video data, a one-way analysis of variance (ANOVA) is conducted to identify whether any statistically significant changes in population occur during the study period.

Questions 3.1, 3.2, 3.3 and 3.4 are explored in chapter 3 using a Shannon Diversity Index approach based on taxonomic grouping of organisms that are established in Chapter 2. Using diversity Indices, statistical significance correlations are identified among abundance, diversity and several other potential environmental drivers: depth, current velocity and variability, bottom water salinity, nutrients and chlorophyll concentrations, and sediment grain size, chlorophyll a, carbon and nitrogen content. Results from this statistical analysis are used to make predictions on how abundance and diversity of epibenthic species in Barrow Canyon may shift with projected changes in the Canyon's environmental conditions.

Chapter 4 further frames the relationship between epibenthic abundance, diversity and environmental drivers in Barrow Canyon in light of broader changes in the Pacific Arctic region. This chapter also includes concluding remarks and outlines future uses of the sampling approach.

References

- Armitage, T. W. K., Manucharyan, G. E., Petty, A. A., Kwok, R., & Thompson, A. F. (2020). Enhanced eddy activity in the Beaufort Gyre in response to sea ice loss. *Nature Communications*, *11*(1). <https://doi.org/10.1038/s41467-020-14449-z>
- Bluhm, B. A., & Gradinger, R. (2008). Regional variability in food availability for Arctic marine mammals. *Ecological Applications*, *18*(sp2), S77–S96. <https://doi.org/10.1890/06-0562.1>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F. J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., & Olsen, M. S. (2019). Key indicators of Arctic climate change: 1971-2017. In *Environmental Research Letters* (Vol. 14, Issue 4). Institute of Physics Publishing. <https://doi.org/10.1088/1748-9326/aafc1b>
- Carmack, E., & Wassmann, P. (2006). Food webs and physical–biological coupling on pan-Arctic shelves: Unifying concepts and comprehensive perspectives. *Progress in Oceanography*, *71*(2–4), 446–477. <https://doi.org/10.1016/j.pocean.2006.10.004>
- Coachman, L. K., Aagaard, K., & Tripp, R. B. (1975). Bering Strait: The regional physical oceanography. University of Washington Press.
- Cooper, L. W., & Grebmeier, J. M. (2022). A chlorophyll biomass time-series for the Distributed Biological Observatory in the context of seasonal sea ice declines in the Pacific Arctic region. *Geosciences* *2022*, *12*, 307. <https://doi.org/https://doi.org/10.3390/geosciences120803077>
- Cooper, L. W., Guarinello, M. L., Grebmeier, J. M., Bayard, A., Lovvorn, J. R., North, C. A., & Kolts, J. M. (2019). A video seafloor survey of epibenthic communities in the Pacific Arctic including Distributed Biological Observatory stations in the northern Bering and Chukchi seas. *Deep Sea Research Part II: Topical Studies in Oceanography*, *162*, 164–179. <https://doi.org/10.1016/j.dsr2.2019.05.003>
- Cooper, L. W., Larsen, I. L., Grebmeier, J. M., & Moran, S. B. (2005). Detection of rapid deposition of sea ice-rafted material to the Arctic Ocean benthos using the cosmogenic tracer ^7Be . *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(24–26), 3452–3461. <https://doi.org/10.1016/j.dsr2.2005.10.011>
- Danielson, S. L., Eisner, L., Ladd, C., Mordy, C., Sousa, L., & Weingartner, T. J. (2017). A comparison between late summer 2012 and 2013 water masses, macronutrients, and phytoplankton standing crops in the northern Bering and Chukchi Seas. *Deep Sea*

Research Part II: Topical Studies in Oceanography, 135, 7–26.
<https://doi.org/10.1016/j.dsr2.2016.05.024>

- Danielson, S. L., Hennon, T. D., Hedstrom, K. S., Pnyushkov, A., Polyakov, I., Carmack, E., Filchuk, K., Janout, M., Makhotin, M., Williams, W. J., & Padman, L. (2020). Oceanic routing of wind-sourced energy along the Arctic continental shelves. *Frontiers in Marine Science*, 7. <https://doi.org/10.3389/fmars.2020.00509>
- Danielson, S. L., Weingartner, T. J., Aagaard, K., Zhang, J., & Woodgate, R. A. (2012). Circulation on the central Bering Sea shelf, July 2008 to July 2010. *Journal of Geophysical Research: Oceans*, 117(C10), n/a-n/a.
<https://doi.org/10.1029/2012JC008303>
- Dunton, K. H., Goodall, J. L., Schonberg, S. v., Grebmeier, J. M., & Maidment, D. R. (2005). Multi-decadal synthesis of benthic–pelagic coupling in the western arctic: Role of cross-shelf advective processes. *Deep Sea Research Part II: Topical Studies in Oceanography*, 52(24–26), 3462–3477. <https://doi.org/10.1016/j.dsr2.2005.09.007>
- Filbee-Dexter, K., Wernberg, T., Fredriksen, S., Norderhaug, K. M., & Pedersen, M. F. (2019). Arctic kelp forests: Diversity, resilience and future. *Global and Planetary Change*, 172, 1–14. <https://doi.org/10.1016/j.gloplacha.2018.09.005>
- Frey, K. E., Comiso, J. C., Cooper, L. W., Grebmeier, J. M., & Stock, L. v. (2021). Arctic Ocean primary productivity: The response of marine algae to climate warming and sea ice decline. *Arctic Report Card*. <https://doi.org/10.25923/kxhb-dw16>
- Garrison, G. R., & Becker, P. (1976). The Barrow submarine Canyon: A drain for the Chukchi Sea. *Journal of Geophysical Research*, 81(24), 4445–4453.
<https://doi.org/10.1029/JC081i024p04445>
- Goethel, C. L., Grebmeier, J. M., & Cooper, L. W. (2019). Changes in abundance and biomass of the bivalve *Macoma calcarea* in the northern Bering Sea and the southeastern Chukchi Sea from 1998 to 2014, tracked through dynamic factor analysis models. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 127–136.
<https://doi.org/10.1016/j.dsr2.2018.10.007>
- Goldsmid, J., Schlegel, R. W., Filbee-Dexter, K., MacGregor, K. A., Johnson, L. E., Mundy, C. J., Savoie, A. M., McKindsey, C. W., Howland, K. L., & Archambault, P. (2021). Kelp in the eastern Canadian Arctic: Current and future predictions of habitat suitability and cover. *Frontiers in Marine Science*, 18.
<https://doi.org/10.3389/fmars.2021.742209>

- Gong, D., & Pickart, R. S. (2015). Summertime circulation in the eastern Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 118, 18–31. <https://doi.org/10.1016/j.dsr2.2015.02.006>
- Graf, G., & Rosenberg, R. (1997). Bioresuspension and biodeposition: a review. *Journal of Marine Systems*, 11(3–4), 269–278. [https://doi.org/10.1016/S0924-7963\(96\)00126-1](https://doi.org/10.1016/S0924-7963(96)00126-1)
- Grebmeier, J. M. (2012). Shifting patterns of life in the Pacific Arctic and sub-Arctic Seas. *Annual Review of Marine Science*, 4, 63–78. <https://doi.org/10.1146/annurev-marine-120710-100926>
- Grebmeier, J. M., Frey, K., Cooper, L., & Kędra, M. (2018). Trends in benthic macrofaunal populations, seasonal sea ice persistence, and bottom water temperatures in the Bering Strait region. *Oceanography*, 31(2). <https://doi.org/10.5670/oceanog.2018.224>
- Grebmeier, J. M., & McRoy, P. C. (1989). Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. III. Benthic food supply and carbon cycling. *Marine Ecology Progress Series*, 53(1), 79–91. <http://www.jstor.org/stable/24834380>
- Grebmeier, J. M., Moore, S. E., Cooper, L. W., & Frey, K. E. (2019). The Distributed Biological Observatory: A change detection array in the Pacific Arctic – An introduction. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 1–7. <https://doi.org/10.1016/j.dsr2.2019.05.005>
- Grebmeier, J. M., Moore, S. E., Overland, J. E., Frey, K. E., & Gradinger, R. (2010). Biological response to recent Pacific Arctic sea ice retreats. *Eos, Transactions American Geophysical Union*, 91(18), 161. <https://doi.org/10.1029/2010EO180001>
- Hauser, D. D. W., Laidre, K. L., Stern, H. L., Suydam, R. S., & Richard, P. R. (2018). Indirect effects of sea ice loss on summer-fall habitat and behaviour for sympatric populations of an Arctic marine predator. *Diversity and Distributions*, 24(6), 791–799. <https://doi.org/10.1111/ddi.12722>
- Hennon, T. D., Danielson, S. L., Woodgate, R. A., Irving, B., Stockwell, D. A., & Mordy, C. W. (2022). Mooring measurements of Anadyr Current nitrate, phosphate, and silicate enable updated Bering Strait nutrient flux estimates. *Geophysical Research Letters*, 49(16). <https://doi.org/10.1029/2022GL098908>
- Hill, V. J., Matrai, P. A., Olson, E., Suttles, S., Steele, M., Codispoti, L. A., & Zimmerman, R. C. (2013). Synthesis of integrated primary production in the Arctic Ocean: II. In situ and remotely sensed estimates. *Progress in Oceanography*, 110, 107–125. <https://doi.org/10.1016/j.pocean.2012.11.005>

- Iken, K., Mueter, F., Grebmeier, J. M., Cooper, L. W., Danielson, S. L., & Bluhm, B. A. (2019). Developing an observational design for epibenthos and fish assemblages in the Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 180–190. <https://doi.org/10.1016/j.dsr2.2018.11.005>
- Jay, C., Fischbach, A., & Kochnev, A. (2012). Walrus areas of use in the Chukchi Sea during sparse sea ice cover. *Marine Ecology Progress Series*, 468, 1–13. <https://doi.org/10.3354/meps10057>
- Krumbein, W. C. (1934). Size frequency distributions of sediments. *SEPM Journal of Sedimentary Research*, Vol. 4. <https://doi.org/10.1306/D4268EB9-2B26-11D7-8648000102C1865D>
- Lu, X., Xu, J., Xu, Z., & Liu, X. (2021). Assessment of benthic ecological quality status using multi-biotic indices based on macrofaunal assemblages in a semi-enclosed bay. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.734710>
- Moore, S. E., Logerwell, E., Eisner, L., Farley, E. v., Harwood, L. A., Kuletz, K., Lovvorn, J., Murphy, J. R., & Quakenbush, L. T. (2014). Marine fishes, birds and mammals as sentinels of ecosystem variability and reorganization in the Pacific Arctic region. In *The Pacific Arctic Region* (pp. 337–392). Springer Netherlands. https://doi.org/10.1007/978-94-017-8863-2_11
- Mountain, D. G., Coachman, L. K., & Aagaard, K. (1976). On the flow through Barrow Canyon. *Journal of Physical Oceanography*, 6(4), 461–470. [https://doi.org/10.1175/1520-0485\(1976\)006<0461:OTFTBC>2.0.CO;2](https://doi.org/10.1175/1520-0485(1976)006<0461:OTFTBC>2.0.CO;2)
- Mueter, F., Iken, K., Cooper, L., Grebmeier, J. M., Kuletz, K., Hopcroft, R., Danielson, S. L., Collins, E., & Cushing, D. (2021). Changes in diversity and species composition across multiple assemblages in the eastern Chukchi Sea during two contrasting years are consistent with borealization. *Oceanography*, 34(2). <https://doi.org/10.5670/oceanog.2021.213>
- Nelson, R. J., Ashjian, C. J., Bluhm, B. A., Conlan, K. E., Gradinger, R. R., Grebmeier, J. M., Hill, V. J., Hopcroft, R. R., Hunt, B. P. V., Joo, H. M., Kirchman, D. L., Kosobokova, K. N., Lee, S. H., Li, W. K. W., Lovejoy, C., Poulin, M., Sherr, E., & Young, K. V. (2014). Biodiversity and biogeography of the lower trophic taxa of the Pacific Arctic region: sensitivities to climate change. In *The Pacific Arctic Region* (pp. 269–336). Springer Netherlands. https://doi.org/10.1007/978-94-017-8863-2_10
- Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A., & Rahmstorf, S. (2002). Increasing river

- discharge to the Arctic Ocean. *Science*, 298(5601), 2171–2173.
<https://doi.org/10.1126/science.1077445>
- Peterson, B. J., McClelland, J., Curry, R., Holmes, R. M., Walsh, J. E., & Aagaard, K. (2006). Trajectory shifts in the Arctic and Subarctic freshwater cycle. *Science*, 313(5790), 1061–1066. <https://doi.org/10.1126/science.1122593>
- Pickart, R. S., Spall, M. A., Lin, P., Bahr, F., McRaven, L. T., Arrigo, K. R., & Grebmeier, J. M. (2021). Physical controls on the macrofaunal benthic biomass in Barrow Canyon, Chukchi Sea. *Journal of Geophysical Research: Oceans*, 126(5).
<https://doi.org/10.1029/2020JC017091>
- Rand, K., Logerwell, E., Bluhm, B., Chenelot, H., Danielson, S. L., Iken, K., & Sousa, L. (2018). Using biological traits and environmental variables to characterize two Arctic epibenthic invertebrate communities in and adjacent to Barrow Canyon. *Deep Sea Research Part II: Topical Studies in Oceanography*, 152, 154–169.
<https://doi.org/10.1016/j.dsr2.2017.07.015>
- Reynolds, O. (1883). An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Philosophical Transactions of the Royal Society of London*, 174, 935–982. <https://doi.org/10.1098/rstl.1883.0029>
- Sebens, K., Sarà, G., & Nishizaki, M. (2017). Energetics, particle capture, and growth dynamics of benthic suspension feeders. In *Marine Animal Forests* (pp. 1–42). Springer International Publishing. https://doi.org/10.1007/978-3-319-17001-5_17-3
- Snelgrove, P. V. R. (1998). The biodiversity of macrofaunal organisms in marine sediments. *Biodiversity and Conservation*, 7(9), 1123–1132.
<https://doi.org/10.1023/A:1008867313340>
- Stabeno, P. J., Bell, S., Cheng, W., Danielson, S. L., Kachel, N. B., & Mordy, C. W. (2016). Long-term observations of Alaska Coastal Current in the northern Gulf of Alaska. *Deep Sea Research Part II: Topical Studies in Oceanography*, 132, 24–40.
<https://doi.org/10.1016/j.dsr2.2015.12.016>
- Stabeno, P. J., Kachel, N., Ladd, C., & Woodgate, R. A. (2018). Flow patterns in the Eastern Chukchi Sea: 2010–2015. *Journal of Geophysical Research: Oceans*, 123(2), 1177–1195. <https://doi.org/10.1002/2017JC013135>
- Timmermans, M. L., & Marshall, J. (2020). Understanding Arctic Ocean circulation: a review of ocean dynamics in a changing climate. *Journal of Geophysical Research: Oceans*, 125(4). <https://doi.org/10.1029/2018JC014378>

- Waga, H., Eicken, H., Hirawake, T., & Fukamachi, Y. (2021). Variability in spring phytoplankton blooms associated with ice retreat timing in the Pacific Arctic from 2003–2019. *PLOS ONE*, *16*(12), e0261418. <https://doi.org/10.1371/journal.pone.0261418>
- Weingartner, T. J., Aagaard, K., Woodgate, R. A., Danielson, S. L., Sasaki, Y., & Cavalieri, D. (2005). Circulation on the north central Chukchi Sea shelf. *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(24–26), 3150–3174. <https://doi.org/10.1016/j.dsr2.2005.10.015>
- Weingartner, T. J., Cavalieri, D., Aagaard, K., & Sasaki, Y. (1998). Circulation, dense water formation, and outflow on the northeast Chukchi shelf. *Journal of Geophysical Research*, *103*, 7647–7661.
- Wood, K. R., Bond, N. A., Danielson, S. L., Overland, J. E., Salo, S. A., Stabeno, P. J., & Whitefield, J. (2015). A decade of environmental change in the Pacific Arctic region. *Progress in Oceanography*, *136*, 12–31. <https://doi.org/10.1016/j.pocean.2015.05.005>
- Woodgate, R. A. (2018). Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data. *Progress in Oceanography*, *160*, 124–154. <https://doi.org/10.1016/j.pocean.2017.12.007>
- Woodgate, R. A., Aagaard, K., & Weingartner, T. J. (2005). A year in the physical oceanography of the Chukchi Sea: Moored measurements from autumn 1990–1991. *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(24–26), 3116–3149. <https://doi.org/10.1016/j.dsr2.2005.10.016>
- Woodgate, R. A., & Peralta-Ferriz, C. (2021). Warming and freshening of the Pacific Inflow to the Arctic from 1990-2019 implying dramatic shoaling in Pacific winter water ventilation of the Arctic Water column. *Geophysical Research Letters*, *48*(9). <https://doi.org/10.1029/2021GL092528>

Tables

Table 1.1 Latitude, longitude, and average approximate depth for the ten stations samples at DBO5.

| Station | Latitude (°N) | Longitude (°W) | Average Approximate Depth (m) |
|----------------|----------------------|-----------------------|--------------------------------------|
| BarC1 | 71.248 | -157.163 | 45 |
| BarC2 | 71.288 | -157.247 | 55 |
| BarC3 | 71.331 | -157.33 | 90 |
| BarC4 | 71.373 | -157.412 | 110 |
| BarC5 | 71.41 | -157.488 | 121 |
| BarC6 | 71.455 | -157.579 | 108 |
| BarC7 | 71.498 | -157.659 | 81 |
| BarC8 | 71.536 | -157.757 | 69 |
| BarC9 | 71.577 | -157.839 | 62 |
| BarC10 | 71.619 | -157.925 | 60 |

Figures

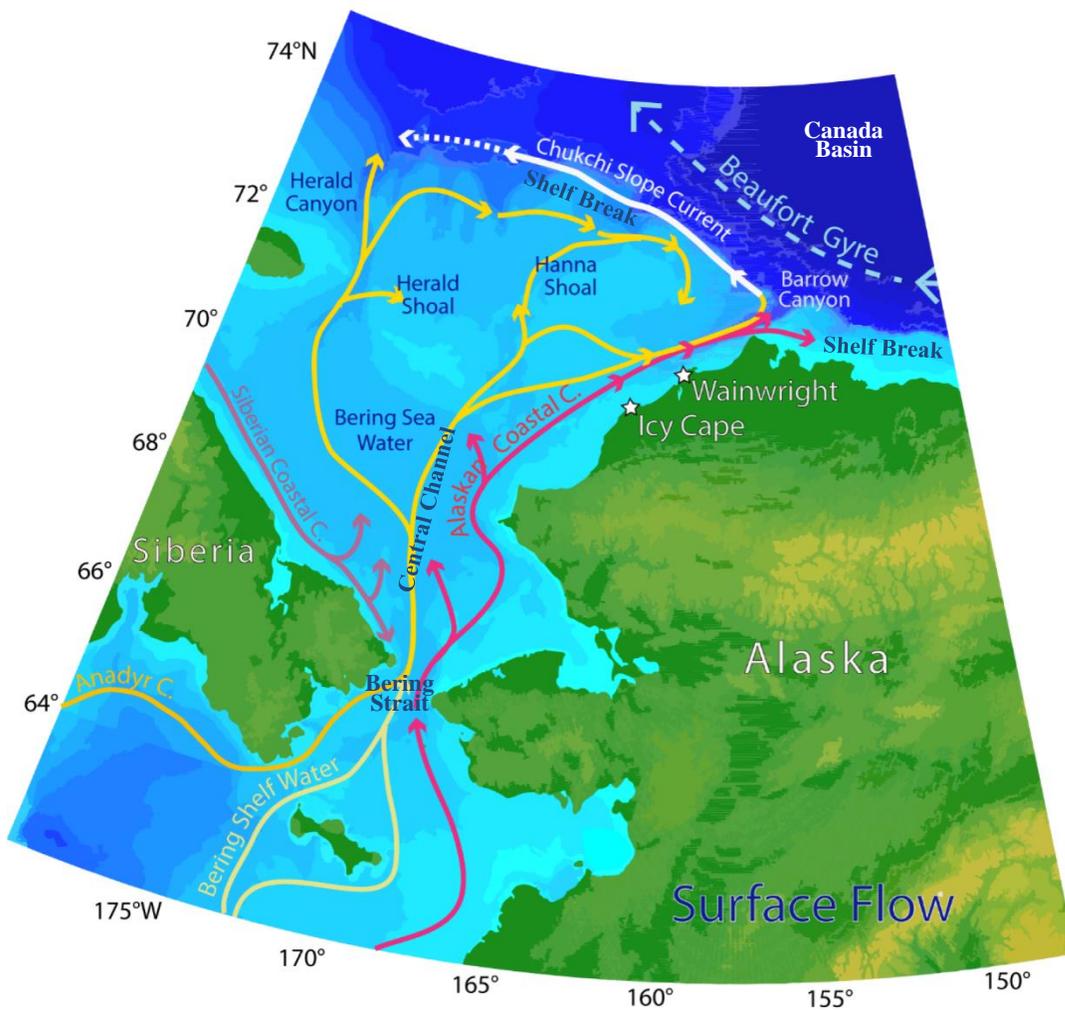


Figure 1.1 A Map of the various branches of prevailing currents in the Pacific Arctic as well as features of importance across the Sub-Arctic and Pacific Arctic regions (Adapted from Stabeno et al. 2018).



Figure 1.2 A map of the eight sampling regions that make up the Distributed Biological Observatory (DBO) extending from the northern Bering Sea, through the Chukchi Sea and into the Beaufort Sea. Each red bounding box represents a ‘hotspot’ of biological productivity and biodiversity while the red points are sampling transects within each DBO region. Maximum and minimum median ice extent based on Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMIS) satellite-derived sea-ice concentrations (1980–2018) are also shown on this figure (Figure from Grebmeier et al. 2019).

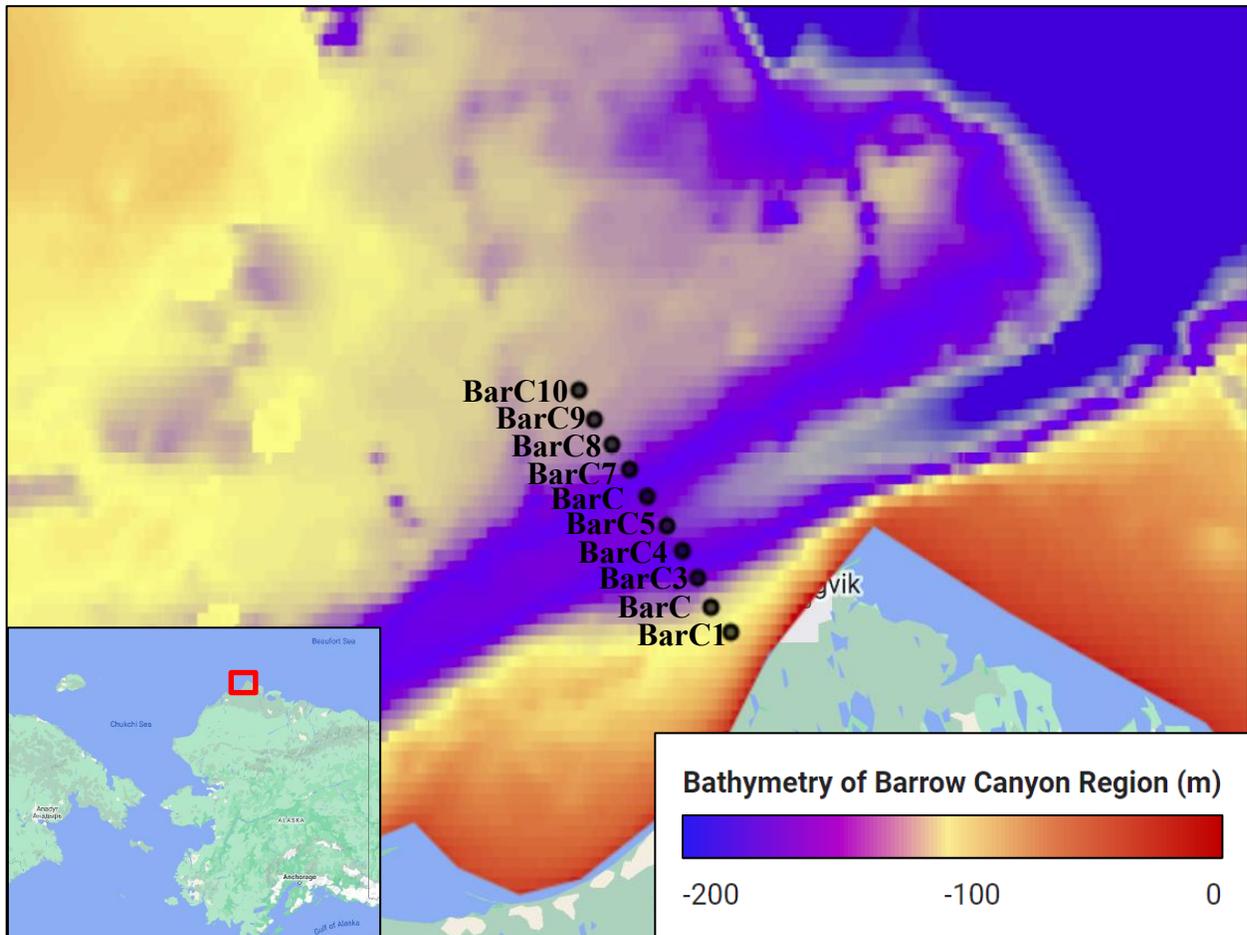


Figure 1.3 A map of the ten stations that make up the DBO5 sampling transect made with Google Earth Engine and related datasets. The bathymetry of the region is visualized with the color bar which denotes to scale from 200m depth to surface (Amante & Eakins, 2009). The ten stations (BarC1-BarC10) are denoted by the black dots and labeled.

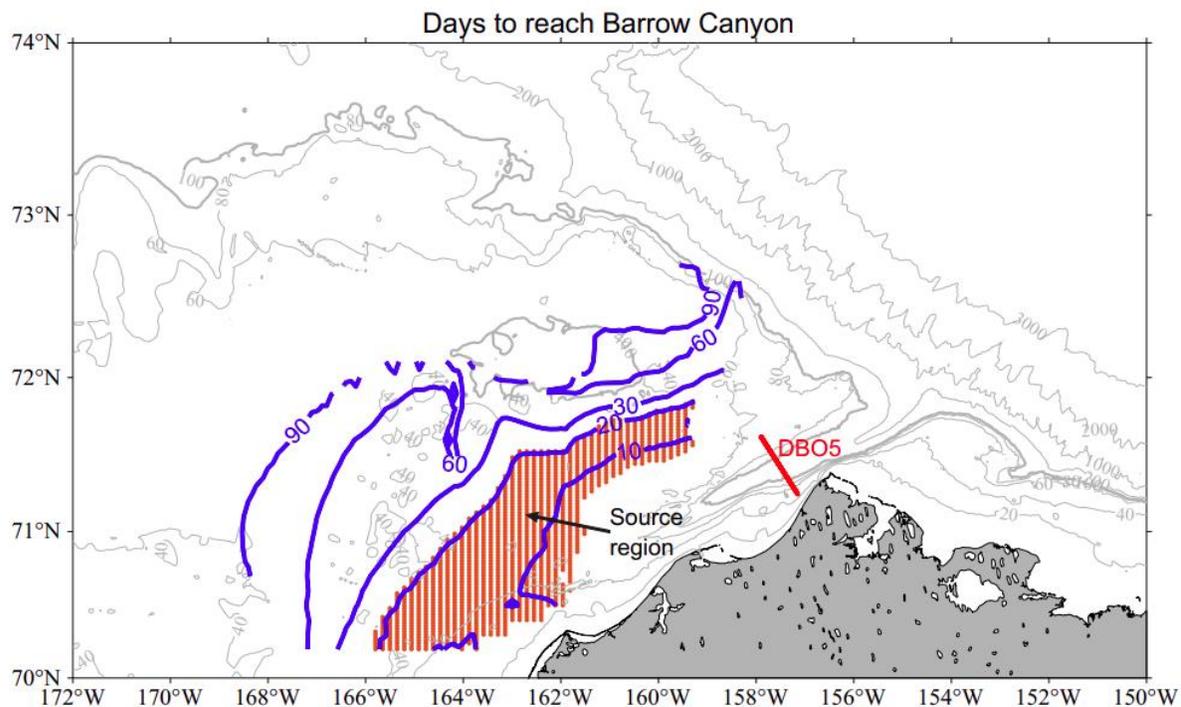


Figure 1.4 A map of elapsed time in days for simulated point source tracers to reach the DBO5 transect from the Chukchi shelf. The blue contours show days elapsed while the red hatching denotes the period of 7–21 days, corresponding to the most pertinent source region of Chlorophyll-*a* to the pycnocline in Barrow Canyon (Figure from Pickart et al., 2021).

Chapter 2: Integrating Drop Camera Video Data into the Distributed Biological Observatory Sampling Effort

1. Introduction

1.1 The Need for Robust Sampling in a Changing Pacific Arctic

Additional documentation of ecosystem shifts is necessary for understanding current trends and predicting future biological implications of the changing climate in the Arctic and surrounding regions (Box et al., 2019; Grebmeier, 2012; Grebmeier et al., 2010; Hauser et al., 2018; Wood et al., 2015). To accomplish this goal, there must be sampling of the physical, chemical and biological aspects of the Arctic Ocean as well as a continued evaluation of current sampling techniques and implementation of new ones where there are gaps in current sampling efforts. The Distributed Biological Observatory (DBO) is an internationally coordinated Pacific Arctic data sharing network aimed at providing long-term biological, chemical, and physical sampling that assesses changes in the biological community as seasonal sea ice declines (Grebmeier et al., 2019). In the Pacific Arctic, the DBO is made up of eight sampling areas (DBO1-DBO8) each containing sampling transects (Figure 1.2). The bounding boxes for these sampling areas contain ‘hotspots’ of biological productivity and biodiversity that have been previously identified (Grebmeier et al., 2019). Combined, the DBO sampling areas serve as a change detection array extending from the northern Bering Sea through the Chukchi Sea and into the Beaufort Sea. Sampling techniques used within the DBO research network include, but are not limited to, Conductivity Temperature and Depth (CTD) Profilers, Acoustic Doppler Current Profilers (ADCP), water column measurements, and sediment collections using Van Veen Grabs to collect infauna samples. Periodic trawling is also used in the sampling region to catalog epibenthic species where that is practical given sediment composition and depth (Danielson et al., 2022). Because trawling can be limited over hard seafloor substrates, is time-consuming and requires an appropriate ship platform,

identifying and standardizing other means of epibenthic sampling are important for fully documenting epibenthic communities as part of the DBO's sampling efforts.

1.2 The Drop Camera Video System Sampling Technique

Underwater imaging is a powerful tool and an increasingly prevalent form of marine sampling. There are many unique benefits of image sampling in contrast with traditional epibenthic oceanographic methods such as grabs or trawls, including the ability to continually refer to the original sample which is unaltered by time or preservation methods (Bethoney & Stokesbury, 2018). For benthic imaging specifically, the decreased impact and disturbance to benthic habitats as well as the enhanced ability to understand epifaunal patterns makes it a superior sampling method for many studies (de Mendonça & Metaxas, 2021). While underwater imaging is by no means a new phenomenon (e.g. Longley & Martin, 1927), the decreasing cost of both imaging equipment and data storage have made this technology more widespread in the marine community (Clayton & Dennison, 2017). The field of marine imaging has also undergone a diversification of imaging equipment including remote operated underwater vehicles (ROVs), camera sleds, long term stationary camera mounts and drop camera video systems (Cazenave et al., 2014; de Mendonça & Metaxas, 2021). Thus, the decrease in costs and increased capability of imaging types and methods have expanded the affordability, accessibility, and applicability of subsea imaging.

Considering these benefits, a Drop Camera Video System (DCVS) has been used in the Pacific Arctic Region aboard the CCGS Sir Wilfrid Laurier as a practical means for sampling the epibenthos in the DBO (Cooper et al., 2019). This initial study indicated that additional improvements could be made to standardize collection and processing of video data, and in the end to make the video imagery a more robust sampling technique that could contribute to time

series data. This chapter outlines standardized operating procedures for the collection and processing of video imagery as well as a procedural example of how the data from the Barrow Canyon region (DBO5) can be used to enhance epibenthic analysis and interpretation of other data streams. Located off Utqiagvik, Alaska, DBO5 consists of ten stations across Barrow Canyon (BarC), specifically BarC1-BarC10 that form a sampling line perpendicularly transecting the Canyon approximately 60 nautical miles from its head (Figure 2.1, Figure 1.3). The shallowest sampling stations are BarC1 (nearshore) and BarC10 (offshore) that are ~50m and ~60m depth, respectively, while BarC5 is the deepest sampling point at ~125m depth (Table 1.1). This means that the inshore slope of the Canyon is sampled from BarC1-BarC4 while the offshore slope is sampled at BarC6-BarC10. This creates a relatively symmetrical sampling depth profile mirrored around BarC5, which is the deepest sampling station. This transect line was chosen for this study because of the large range of epibenthic organisms across a small area. Video imagery is available from the July occupation of DBO5 stations during 2017, 2019 and 2021. These years coincide with DCVS deployment and ice-free conditions on the DBO5 line during sampling.

1.3 Objective of Study

The objective of this study is to establish best practices and standardized operating procedures for video collection and processing as well as providing a procedural example and representative results of how the collected data can be analyzed (Bethoney & Stokesbury, 2018). The purpose of this methodical standardization is to better incorporate video camera data into more robust sampling methods for the DBO. These data also fill a gap in epibenthic community characterization by providing imagery in areas where trawling is not practical due to bottom sediment composition, depth, and an appropriate ship platform and ship time. Video data also creates the potential to better understand within station distribution of species that cannot be fully

explored through trawling. Therefore, video imagery can provide time-series epibenthic data that cannot be otherwise acquired in a region where documenting biological changes in the context of climate change is of increasing importance.

1.4 Statement of Objectives, Justification, and Hypotheses

The following statements are numbered to match their listing in Chapter 1 and listed again in Chapter 2.

2.1 Establish standard operating procedures for the collection and analysis of drop camera video data in the Pacific Arctic region.

Purpose 2.1 To standardize collection and processing so data can be used for future time series analysis and other DBO research efforts.

2.2 Determine which epibenthic organisms can be identified with reasonable accuracy and establish groupings of organisms based on taxonomic levels.

Purpose 2.2 To establish organisms that can be tracked year to year to provide time series data for future research and to prime data to be used for Diversity Index Calculations.

2.3 What is the abundance of these target organisms through the years of available data at DBO5?

Hypotheses 2.3 The overall abundance of epibenthic organisms reaches a maximum in the center of Barrow Canyon (BarC5), due to organic particulate settling and availability. Abundance of organisms will decrease up both the inshore (BarC1-BarC4) and offshore (BarC6-BarC10) slopes of the Canyon in the transition upslope into shallower waters.

2.4 Are there statistically significant differences in the abundance of key species across the study period at DBO5?

Hypotheses 2.4 In the three years of available data (2017, 2019 and 2021) there are no statistically significant changes in the overall abundance of epibenthic organisms, but certain taxonomic groups will experience statistically significant shifts in abundance at certain stations due to varying environmental drivers.

2. Materials and Methods

2.1 Image Processing and Data Collection

The DCVS used aboard the CCGS Sir Wilfrid Laurier was manufactured by A.G.O. Environmental Electronics Ltd. in Victoria, B.C., Canada. The DCVS suite is deck deployed via an electronic load bearing cable that transmits a live video feed to a shipboard computer where video can be recorded and saved. Onboard the DCVS suite is an underwater pressure rated camera, artificial light source, measurement position lasers, a thermometer and a pressure transducer. For additional information on the camera suite, deployment setup and protocols, as well as video collection software and storage, see Appendix 1.

To process the video data, .mp4 format files are first imported into Adobe Premiere Pro video editor software (www.adobe.com/prodcuts/premiere.html). The videos are put into a 720x480 standard definition sequence in the *Timeline* window that preserves their original aspect ratio. Then, using the *Program* window, still images are exported at 10 second intervals for the duration of the 10 min video clip, yielding 60 images per station (Figure 2.2). Therefore, our three sampling years (2017, 2019 and 2021), are associated with a total of 300 minutes of video data that yielded 1,800 images for analysis. Exporting still frames from the videos rather than

screenshotting the playback preserves image quality and ensures that the frames' pixel aspect ratio is standardized throughout the data, which is necessary for area analysis. Each still is saved with the station name and still number (1-60) to allow for accurate reference to specific images.

Once the image data are finalized and saved, abundance counts are undertaken. Organisms that are partially in frame and out of frame are counted if $\geq 50\%$ of the organism is visible within the frame. For example, if two or more legs of Ophiuroidea (brittle star) are entirely visible within frame, the organism is counted. Abundance counts are recorded and saved for each image individually so a specific frame and organism can be directly referenced. Sum abundances are then calculated and saved for each station.

Images are also imported into Image Processing and Analyzing in Java or ImageJ/Fiji (<https://imagej.nih.gov/ij/>). ImageJ is an open-source versatile image processing software hosted by the US National Institutes of Health which has been popularized for biological-image analysis (Schindelin et al., 2012). It has also been used specifically for benthic image processing for both biology and sediments (Solé et al., 2007). For this analysis ImageJ is used to measure pixel distance between the two laser points in each frame. Measurements are then stored as a data matrix via ImageJ and exported as a comma separated value (.csv) file for each station. Using the known distance of 10 cm between the laser points and the pixel distance between the points in the frame analyzed, the pixel to length ratio is calculated from each frame. Then, with the known pixel aspect ratio of 720x480, the area viewed within each frame is determined for every image. At each station, the total abundance count for each organism is then divided by the area viewed at that station to calculate abundance as individuals per m^2 (ind/ m^2). This allows for cross-station and cross-year comparisons of abundance despite the variability of area analyzed that is inherent in drop camera video data, which varies in its height above the seafloor.

2.2 Statistical Analysis

As a part of method standardization, we provide an example of initial statistical analysis that can be performed on drop camera video data, including tests for population normality and several one-way analyses of variance tests (ANOVA) both with a significance level of $\alpha=0.05$. The test used for normality is the Shapiro-Wilk test which is used for small sample sizes of $N<50$. These data have a sample size of $N=30$, which makes this an appropriate analysis. The null hypothesis (H_0) for a Shapiro-Wilk test is that the population is normally distributed while the alternative hypothesis (H_a) is that the population is non-normally distributed. The assumptions for the one-way ANOVA tests are 1) population normality, 2) sample independence and 3) homoscedasticity or the homogeneity of variance. The H_0 of a one-way ANOVA is that there is no difference in the population means while the H_a is that there is a difference in the population means.

These tests will determine the normality of distribution and if there are statistically significant differences year to year in both the overall abundance and abundance of predominant taxa. First, to test for the standardization of data year to year, a one-way ANOVA is performed on the “northing” variable which denotes the km from the pole of each station. This ensures that slight variability year to year in the latitude and longitude of the sampling station does not result in statistically significantly different sampling locations. Shapiro-Wilk Normality tests are then performed on overall average abundance of the three study years to determine if abundance is normally distributed around the trough of the Canyon. Finally, one-way ANOVA tests are performed on the overall abundance of different feeding types and abundance of predominant taxa for 2017, 2019 and 2021 to test if there are any shifts in the mean abundance across the canyon from 2017 to 2021.

3. Results

3.1 Target Organisms

Target organisms are briefly described in Table 2.1 along with their taxonomic class, feeding classification, and a reference photo. There are fifteen groupings of organisms that can be identified with reasonable accuracy that belong to eight taxonomic classes. Both the groupings (order or class) and the taxonomic class are provided as each can be used for different research goals. The more specific organism grouping is used for year-to-year comparisons of that specific organism while the standardized taxonomic level of class allows for Shannon-Weaver Diversity Index calculations and comparisons. Feeding classifications are also provided as they are used to determine the distribution of certain feeding types, e.g. deposit, suspension, scavengers, etc.

Ophiuroidea, or brittle stars, are the most predominant organisms identified in the DBO5 data that are analyzed as a part of this study. Their adult body size can range from 2.0 to 200 mm and they are characterized by 5 dexterous limbs and a solid endoskeleton (Stöhr et al., 2022). They can engage in suspension or deposit feeding depending on environmental conditions and are voracious feeders. *Ophiuroidea* food sources include algae, detritus and zooplankton.

3.2 Abundance of Organism groups and Taxonomic classes

Abundance of organisms counted across the DBO5 transect peaks at BarC6 with an average of ~700 individuals per m² during the three sampling years (Table 2.2). Abundance decreases from BarC6 towards the shallowest sampling stations, which are BarC1 and BarC10 with the notable exception of BarC3. BarC3 abundance counts varied dramatically during the sampling years with abundance of 1778 individuals per m² (ind/m²) during 2017 and 33 ind/m² and 59 ind/m² during 2019 and 2021, respectively. The predominant organism at BarC3, which drive the differences in

individuals per m² during the study years, is *Elasipodida (O. glacialis)*, which is a member of Holothuroidea (sea cucumbers) (Table 2.1). The higher abundance of *Elasipodida (O. glacialis)* during 2017 causes a skewed average abundance per m² at BarC3. If the 2017 data point is removed from the data, the average at BarC3 is ~46 ind/m². This value fits into the general trend of abundance peaking at BarC6 with decreasing abundances at each station towards both BarC1 and BarC10 (Figure 2.3).

The predominant taxa at DBO5 are Ophiuroidea, brittle stars (Figure 2.4). The average Ophiuroidea abundance peaks at BarC6 with 672 ind/m² and decreases in abundance to BarC3 and BarC10 with 2 ind/m² and 20 ind/m², respectively (Table 2.2). Ophiuroidea are not present at BarC1 and BarC2. Ophiuroidea are the dominant taxa at BarC5-BarC10 and appear to be the only organism that peaks in abundance at BarC6. The remainder of the organisms peak in abundance at locations between BarC1-BarC4.

3.3 Abundance of Feeding Types

To explore the distribution of benthic feeding types in Barrow Canyon, the fifteen groupings of organisms are divided into feeding classifications (Table 2.1). The feeding types observed are suspension feeders, deposit feeders, organisms that engage in either suspension or deposit feeding depending on environmental conditions, and organisms that engage in other feeding behaviors, such as scavengers (Table 2.1). Utilizing three of the four feeding classifications (deposit, suspension, and both), the abundance data are used to calculate the average proportion of feeding types at each DBO5 station (Figure 2.5). Organisms that engage in other feeding methods are excluded from this calculation for simplification. For example, Euphausiacea are pelagic zooplankton feeders and are therefore not directly comparable to the benthic feeders.

Organisms that are strictly suspension feeders are dominant at BarC1, BarC2 and BarC4 and their dominance is highest at BarC2 (Figure 2.5). Organisms that are strictly deposit feeders are not dominant at any station; however, they are the most common at BarC1. Organisms that can engage in both suspension and deposit feeding are the most dominant across the Canyon specifically at BarC3 and BarC5-BarC10. The organisms that are the source of this dominance at BarC3 are Elaspodida (*O. glacialis*) while the dominance at BarC5-BarC10 is from Ophiuroidea (Table 2.2).

3.4 Statistical Analysis of Organismal Abundance

The initial statistical analysis was performed using the abundance data collected via the DCVS. This data, as is the case with all video-collected data, presents a statistical challenge because of the limited data set as well as spatial variability within each video and from year to year. Acknowledging these limitations, we calculated northing (distance from the North Pole, 90°N) for each station across the three years and performed an analysis of variance (one-way ANOVA) with a significance level of $\alpha=0.05$ as part of this analysis. This analysis showed that there was not a statistically significant difference in the northing of the ten stations throughout the study period (Table 2.3).

With a further recognition of the uncertainty inherent in performing statistical analysis on this data set and the conclusions we can draw from the analysis; I performed a series ANOVAs with a significance level of $\alpha=0.05$ on the abundance data taken throughout the study period. There was no statistically significant change found in the overall abundance in individuals per m² throughout the study period as well as in the abundance in individuals per m² of each feeding type (Table 2.3). However, there were some organism groupings that experienced statistically

significant shifts during the period from 2017-2021 including Alcyonacea, Gastropoda and Decapoda (Table 2.3). Organisms that did not show statistically significant changes in abundance include Ophiuroidea, Dendrochirotida and Actiniaria (Table 2.1, Table 2.3).

I also performed two normality tests with a significance level of $\alpha=0.05$ on population distribution: one on the average overall abundance of organisms, and one on the average abundance of the dominant taxa at DBO5, which is Ophiuroidea (Table 2.2). The overall abundance of organisms was shown to be normally distributed across the Canyon while the Ophiuroidea were not normally distributed across the Canyon (Table 2.3)

4. Discussion

4.1 Overview

The development of standard operating and processing procedures as well as the procedural example and representative results collected at DBO5, successfully accomplished two objectives designed for the study. Objective 2.1, to enable uniform processing of video data to promote their use for future time-series analysis and other DBO research efforts, is realized via development of a best practices protocol for collection, counting and analysis. Objective 2.2, to identify the organisms that can be tracked year to year to provide time-series data for future research and to provide data to be used for Diversity Index Calculations, is achieved via the analysis of the initial years of DBO5 data which show the fifteen groupings of organisms that can be identified with reasonable accuracy.

The two hypotheses developed by this thesis are also supported and further informed by the data collected at DBO5 during the study years. Hypotheses 2.3 tested whether the overall abundance of epibenthic organisms reaches a maximum at the center of the axis of Barrow Canyon

(BarC5) and decreases bi-directionally up both the inshore and offshore slope. The results indicated that this hypothesis must be amended by results that show a peak in abundance at BarC6 rather than BarC5. However, as predicted, there is a bi-directional decrease in abundance from the station with highest abundance towards BarC1 and BarC10. Finally, Hypotheses 2.4 tested whether there had been no statistically significant changes in the overall abundance of epibenthic organisms, but for certain taxonomic groups, statistically significant shifts in abundance were observed at certain stations, as supported by the results that are presented. This suggests a reorganization of epibenthic composition rather than an overall shift in epibenthic abundance. Further analysis on both the procedural methods and results are discussed below.

4.2 Standardization of Video Data Collections

Standardization of the collection and processing of drop camera video data will harmonize and maximize the value of an additional data set to the DBO sampling program. By establishing standard procedures for imaging the video data and a list of organisms that can be identified with reasonable accuracy within those images, I have enabled the DCVS to be used for future epibenthic time series analysis. These standard operating procedures will enable a multi-member scientific team to process and enumerate abundance from videos without compromising continuity that is crucial for comparing data on a station to station and year to year basis. This will ideally streamline data production to the point that there are sufficient data to perform more robust and lengthier time-series analysis. This will allow for a greater understanding of the epibenthic biology in the region, especially in areas where trawling and other sampling methods for the epibenthos are impractical.

A crucial aspect in my standardization of analysis procedures is the use of the open-source software ImageJ to calculate the area viewed within the images exported from each station's video file. This step allows for the more accurate comparison of data. As mentioned previously, there is statistical complexity inherent in video data because of the variability of area viewed within a station and the inability to prevent a specific area from being viewed multiple times. However, the area calculations enabled by ImageJ are an essential first step in making drop camera video data a more scientifically sound data set for statistical analysis.

Operating procedures outlined in this chapter have been optimized specifically for the capabilities and layout of the Canadian Coast Guard Ship the Sir Wilfrid Laurier and may need to be adapted if the system is used aboard another vessel. Differences in the station keeping abilities of another ship or the indoor facilities in proximity to the deployment location will determine if these procedures are applicable. However, while utilizing the system off another ship may alter the deployment method, the processing and analysis of the data will remain the same, again ensuring that the data is as standardized as possible to increase the proportion of usable footage (data) available for future analysis.

4.3 Procedural Example and Representative Results

An example of analysis of abundance in DBO5 highlights the critical features of the Canyon's epibenthic ecosystems and provides insights on several new potential inquiries for the future. The initial visual assessment of the abundance per m² across DBO5 shows that abundance peaks near the center of the Canyon and abundance decreases bidirectionally up each slope (Figure 2.3). This inference is confirmed by the statistical analysis that suggests the overall abundance per m² is normally distributed around the trough of the Canyon indicating that depth is a prominent

driver of abundance in the Canyon (Table 2.3). However, the distribution pattern of individual species is not identical to the distribution of overall abundance. For example, Ophiuroidea, which are the most abundant organisms in the region, peak in abundance at BarC6 and are non-normally distributed across the DBO5 line (Table 2.2, Table 2.3). This indicates that there are additional complexities controlling the distribution of organisms in Barrow Canyon, meaning that further inquiry into the drivers that affect species distribution in contrast to overall abundance are warranted. Correlation analysis between population distribution and selected environmental drivers further explore this question in chapter 3.

The assessment of feeding types in the Canyon also illuminates interesting aspects of the Canyon's epibenthic biology. An initial look at the data suggests that there is no overall trend of feeding type distribution across the Canyon (Figure 2.5). However, upon further analysis of the raw video data, several other patterns are apparent. This is based upon one of the strengths of video data, which is the ability to observe organisms in-situ to better understand how they are interacting with their environment. This allows for analysis that is unavailable from numerical data alone. For example, detailed examination of the videos collected at BarC3 shows that *Elasipodida* (*O. glacialis*) on the seafloor have extended feeding tentacles containing papillae, which in turn secrete an adhesive material to capture particulate detritus (Figure 2.6) (Madsen & Hansen, 1994). The extension of these tentacles indicates that *O. glacialis* are suspension feeding at BarC3 rather than deposit feeding, which they are also capable of doing. If we re-classify *Elasipodida* (*O. glacialis*) as suspension feeders at BarC3, a distinct pattern of feeding type distribution emerges from the data (Figure 2.5). My observations are that suspension feeders dominate the inshore slope of the Canyon while Ophiuroidea, which can deposit or suspension feed, dominate the offshore slope. While I am unable to conclude that Ophiuroidea are deposit feeding at BarC6-BarC10

without additional analysis, such as carbon and nitrogen stable isotopes to determine food sources, it can be assumed that the different environmental conditions along the inshore slope vs the offshore slope of Barrow Canyon leads to the spatial zonation of feeding types shown by the data.

When identifying changes in abundance throughout the study period Elapodida (*O. glacialis*) stands out as an instructive case. As explained in the results, the abundance of Elapodida (*O. glacialis*) in 2017 is dramatically different from the values in 2019 and 2021 with 1778 ind/m² during 2017 and 33 ind/m² and 59 ind/m² during 2019 and 2021, respectively. The cause of this significant change in population between study years is not evident in the data presented in this chapter; however, there are several possible explanations that could be examined as a part of future analysis. It is possible that *O. glacialis* has population cycles in which the abundance spikes at a given multi-year interval. Expanding these data to include additional years would flesh out our understanding of *O. glacialis* population abundance, showing if the population is oscillating and if so, at what interval this cycle occurs. If there is no cycle evident in the expanded temporal analysis it is possible that a storm event or shift in currents brought high numbers of *O. glacialis* to BarC3 specifically in 2017. Using historical remote sensing data, it is possible to examine the weather and currents on and before the time of sampling during 2017 in the region to identify potential events that could cause high volume of *O. glacialis* to be brought to this area. Utilizing additional data presented in chapter 3, I will further explore this question and potential explanations for the existence of this phenomenon.

Apart from the unique case of Elapodida (*O. glacialis*), potential temporal shifts in Barrow Canyon were explored using one-way ANOVA tests. The results of these tests suggest that within the limited time-frame of analysis, there was no statistically significant shift in overall abundance across the Canyon (Table 2.3). However, while there was no shift in the overall

abundance observed at each station in the Canyon, groups of organisms did exhibit population abundance shifts throughout the six-year study period. Among the organisms that significantly shifted are Alcyonacea, Gastropoda and Decapoda. However, both Gastropods and Decapods are highly mobile epifauna which likely contributes to their shifting abundance. In addition, these three organisms are among the less prevalent observed in the Canyon. The three most dominant epibenthic groups (Ophiuroidea, Elasmobranchia, Dendrochirotida) were not observed to have statistically significant variability in abundance from 2017-2021. Therefore, while there may be minor shifts in the composition of species across the DBO5 line, there is no evidence of a major restructuring of Canyon diversity or an overall shift in organism abundance over the time period of these observations. Of course, a time-series analysis utilizing three years of data across a six-year study period is limited, but continued video analysis will create lengthier abundance datasets that can contribute to more robust analysis in the future.

5. Conclusions

The DCVS is a powerful and versatile data sampling technique. It can sample regions when available ship time or infrastructure for trawling is limited or when other challenges are posed. By outlining standard operating procedures, collection methods and analysis approaches for this powerful tool, I have contributed to standardization of video data that can be used to benefit the DBO and enable the expansion of these data to produce informative time series analysis of epibenthic populations in the Pacific Arctic.

The procedural example undertaken with DBO5 data from 2017, 2019 and 2021 not only shows the strength of standardized video data processing procedures, but also provides support for novel insights and identifies further lines for statistical inquiry. The data collected at DBO5 shows

that while the abundance of organisms is normally distributed around BarC6, which is near the axis of the Canyon, the distribution of different organism's groups is not symmetrical across the Canyon. This suggests that different organisms occupy distinct niches across the Canyon and different environmental drivers cause the distribution of species to be skewed towards the inshore or offshore slopes of Barrow Canyon.

Finally, the methods and results above inform not only our understanding of the Barrow Canyon region but increase our ability to utilize video survey data that has been collected in other DBO sampling areas (Figure 1.2). Of particular interest is DBO3, which is located in the extremely biologically productive Bering Strait region (Grebmeier et al., 2019). Future work could expand this analysis not only temporally but spatially to understand how the distribution of epibenthic species is changing in both magnitude and location across the greater Pacific Arctic Region.

References

- Bethoney, N. D., & Stokesbury, K. D. E. (2018). Methods for image-based surveys of benthic macroinvertebrates and their habitat exemplified by the drop camera survey for the Atlantic Sea Scallop. *Journal of Visualized Experiments*, 137. <https://doi.org/10.3791/57493>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F. J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., & Olsen, M. S. (2019). Key indicators of Arctic climate change: 1971-2017. In *Environmental Research Letters* (Vol. 14, Issue 4). Institute of Physics Publishing. <https://doi.org/10.1088/1748-9326/aafc1b>
- Cazenave, F., Kecy, C., Risi, M., & Haddock, S. H. D. (2014). SeeStar: A low-cost, modular and open-source camera system for subsea observations. *2014 Oceans - St. John's*, 1–7. <https://doi.org/10.1109/OCEANS.2014.7003077>
- Clayton, L., & Dennison, G. (2017). Inexpensive video drop-camera for surveying sensitive benthic habitats: applications from glass sponge (Hexactinellida) reefs in Howe Sound, British Columbia. *The Canadian Field-Naturalist*, 131(1), 46–54. <https://doi.org/10.22621/cfn.v131i1.1783>
- Cooper, L. W., Guarinello, M. L., Grebmeier, J. M., Bayard, A., Lovvorn, J. R., North, C. A., & Kolts, J. M. (2019). A video seafloor survey of epibenthic communities in the Pacific Arctic including Distributed Biological Observatory stations in the northern Bering and Chukchi seas. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 164–179. <https://doi.org/10.1016/j.dsr2.2019.05.003>
- Danielson, S. L., Grebmeier, J. M., Iken, K., Berchok, C., Britt, L., Dunton, K., Eisner, L., Farley, E., Fujiwara, A., Hauser, D., Itoh, M., Kikuchi, T., Kotwicki, S., Kuletz, K., Mordy, C., Nishino, S., Peralta-Ferriz, C., Pickart, R., Stabeno, P. J., ... Woodgate, R. A. (2022). Monitoring Alaskan Arctic Shelf ecosystems through collaborative observation networks. *Oceanography*. <https://doi.org/10.5670/oceanog.2022.119>
- de Mendonça, S. N., & Metaxas, A. (2021). Comparing the performance of a remotely operated vehicle, a drop camera, and a trawl in capturing deep-sea epifaunal abundance and diversity. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.631354>
- Grebmeier, J. M. (2012). Shifting patterns of life in the Pacific Arctic and sub-Arctic Seas. *Annual Review of Marine Science*, 4, 63–78. <https://doi.org/10.1146/annurev-marine-120710-100926>

- Grebmeier, J. M., Moore, S. E., Cooper, L. W., & Frey, K. E. (2019). The Distributed Biological Observatory: A change detection array in the Pacific Arctic – An introduction. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 1–7. <https://doi.org/10.1016/j.dsr2.2019.05.005>
- Grebmeier, J. M., Moore, S. E., Overland, J. E., Frey, K. E., & Gradinger, R. (2010). Biological response to recent Pacific Arctic sea ice retreats. *Eos, Transactions American Geophysical Union*, 91(18), 161. <https://doi.org/10.1029/2010EO180001>
- Hauser, D. D. W., Laidre, K. L., Stern, H. L., Suydam, R. S., & Richard, P. R. (2018). Indirect effects of sea ice loss on summer-fall habitat and behaviour for sympatric populations of an Arctic marine predator. *Diversity and Distributions*, 24(6), 791–799. <https://doi.org/10.1111/ddi.12722>
- Longley, W. H., & Martin, C. (1927). The first autochromes from the ocean bottom. *National Geographic*, 12–13.
- Madsen, FJ., & Hansen, B. (1994). Echinodermata Holothurioidea. *Marine Invertebrates of Scandinavia*, 9(1), 143. <https://www.marinespecies.org/aphia.php?p=sourcedetails&id=662>
- Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, M., Pietzsch, T., Preibisch, S., Rueden, C., Saalfeld, S., Schmid, B., Tinevez, J.-Y., White, D. J., Hartenstein, V., Eliceiri, K., Tomancak, P., & Cardona, A. (2012). Fiji: an open-source platform for biological-image analysis. *Nature Methods*, 9(7), 676–682. <https://doi.org/10.1038/nmeth.2019>
- Solé, A., Mas, J., & Esteve, I. (2007). A new method based on image analysis for determining cyanobacterial biomass by CLSM in stratified benthic sediments. *Ultramicroscopy*, 107(8), 669–673. <https://doi.org/10.1016/j.ultramic.2007.01.007>
- Stöhr, S., O’Hara, T., & Thuy, B. (2022). World Ophiuroidea database. Ophiuroidea. *World Register of Marine Species* . <https://www.marinespecies.org/aphia.php?p=taxdetails&id=123084> on 2022-06-15
- Wood, K. R., Bond, N. A., Danielson, S. L., Overland, J. E., Salo, S. A., Stabeno, P. J., & Whitefield, J. (2015). A decade of environmental change in the Pacific Arctic region. *Progress in Oceanography*, 136, 12–31. <https://doi.org/10.1016/j.pcean.2015.05.005>

Tables

Table 2.1 (1/4) Overview of target organisms which can be identified with reasonable accuracy in the drop camera video data. Organisms are broken into four classifications of feeding types including suspension, deposit, organisms that can engage in both suspension and deposit feeding, and organisms that engage in other feeding types such as scavengers.

Images used in the table are pulled or adapted from the following sources:

- a. Ophiuroidea (brittle star) - <https://ucmp.berkeley.edu/2018/12/extreme-competition-species-ocean-floor/>
- b. Phrynophiurida (basket star) - <https://www.marinespecies.org/photogallery.php?album=696&pic=29569>
- c. Asteroidea (sea star) - Oslo Zoological Museum (Naturhistorisk Museum), Oslo, Norway, public domain
- d. Valvatida (sun sea star) - Hillewaert, H.; https://commons.wikimedia.org/wiki/File:Asterias_rubens.jpg
- e. Dendrochirotida (*Psolus*) - <https://www.marinespecies.org/photogallery.php?album=695&pic=139107>
- f. Elaspodida (*O. glacialis*) - <http://www.arcodiv.org/seabottom/Holothurians.html>
- g. Nudibranchia (sea slug) – Skauge C.; <https://www.divephotoguide.com/images/imguploader/91298191.jpg>
- h. Gastropoda (gastropod) - <https://eol.org/pages/590174>
- i. Actiniaria (anemone) - <https://www.arrancoast.com/beadlet-anemone/>
- j. Alcyonacea (soft coral) - George, C. https://www.north-slope.org/wp-content/uploads/2022/04/Sea_raspberry_email_500_615_60.jpg
- k. Scleractinia (hard coral) - Photo courtesy of Tim Shank, Woods Hole Oceanographic Institution and DASS 2005 expedition, National Oceanic and Atmospheric Administration Ocean Exploration, University of Rhode Island, and IFE
- l. Echinoidea (sea urchin) – Hobgood, N.; [https://en.wikipedia.org/wiki/File:Tripneustes_ventricosus_\(West_Indian_Sea_Egg-top\)_and_Echinometra_viridis_\(Reef_Urchin_-_bottom\).jpg](https://en.wikipedia.org/wiki/File:Tripneustes_ventricosus_(West_Indian_Sea_Egg-top)_and_Echinometra_viridis_(Reef_Urchin_-_bottom).jpg)
- m. Stolidobranchia (tunicate) - <https://www.marinespecies.org/photogallery.php?album=669&pic=39021>
- n. Decapoda (crab, hermit crab) - https://en.wikipedia.org/wiki/File:Chionoecetes_bairdi.jpg
- o. Euphausiacea (krill) - <http://www.mesa.edu.au/crustaceans/crustaceans07.asp>

Table 2.1 (1/4)

| Taxonomic Class | Organism (Class or Order) | Picture | Feeding types (suspension, deposit, both suspension and deposit, other) | Description |
|-----------------|-------------------------------|---|---|---|
| Ophiuroidea | Ophiuroidea (brittle star) |  | BOTH | <ul style="list-style-type: none"> - echinoderm (marine invertebrates) - solid endoskeleton - five dexterous adhesive tube feet - five-rayed radial symmetry - adult body size: 2.0 -200mm (Hansson, 2001) |
| | Phrynophiurida (basket stars) |  | SUSPENSION | <ul style="list-style-type: none"> - echinoderm (marine invertebrates) - solid endoskeleton - central disk to 38mm across - the disk is naked with spines on 5 pairs of radial ridges - each arms branch repeatedly - outer parts form a dense tangle (Stöhr et al., 2022) |
| Asteroidea | Asteroidea (sea star) |  | BOTH | <ul style="list-style-type: none"> - echinoderm (marine invertebrates) - solid endoskeleton - five feet - five-rayed radial symmetry - adult body size: 200mm – 600mm (Hayward & Ryland, 1990) - (Smaldon et al., 1993) - (Linnaeus, 1758) |
| | Valvatida (sun sea stars) |  | BOTH | <ul style="list-style-type: none"> - echinoderm (marine invertebrates) - solid endoskeleton - 15 to 24 arms with 15,000 tube feet - heaviest and fastest known sea star: <ul style="list-style-type: none"> - weighing up to 5 kg - moving up to 3 meters per minute (Brusca, 1990) - (Hansson, 2001) |

Table 2.1(2/4) continued

| | | | |
|---------------------------------------|---|-------------------|--|
| <p>Dendrochirofida (psolus)</p> |  <p>e.</p> | <p>SUSPENSION</p> | <ul style="list-style-type: none"> - soft, orange ventral side which is almost perfectly flat and covered in tube feet - dorsal is covered with overlapping calcareous plates which are a reddish-orange color - mouth is located on the dorsal surface - mouth is surrounded by 10 bright red retractable oral tentacles of equal length - adult body size: ≤ 7 cm - (Allen, 1976) - (Carlton, 2007) |
| <p>Elasipodida (O. glacialis)</p> |  <p>f.</p> | <p>BOTH</p> | <ul style="list-style-type: none"> - Soft bodied - Tube feet in lines along body - mouth is located on the dorsal surface - mouth is surrounded by retractable oral tentacles - Many - (Ljungman, 1879) - (Brusca & Brusca, 1990) - (Bisby et al., 2005) |
| <p>Nudibranchia (nudibranch)</p> |  <p>g.</p> | <p>OTHER</p> | <ul style="list-style-type: none"> - soft-bodied marine gastropod molluscs - shed their shells after their larval stage - without true gills - can be very colorful - adult body size: 4 to 600 mm - (Bouchet et al., 2017) |
| <p>Gastropoda (gastropod)</p> |  <p>h.</p> | <p>DEPOSIT</p> | <ul style="list-style-type: none"> - a large foot with a flat sole for crawling - a single coiled shell or a two-half shell that covers the soft body - (Ponder & Lindberg, 1997) |

Table 2.1 (3/4) continued

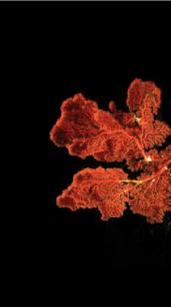
| | | | | |
|-------------------|---------------------------------------|---|-------------------|--|
| | <p>Actiniaria (anemone)</p> |  <p>i.</p> | <p>SUSPENSION</p> | <ul style="list-style-type: none"> - soft bodied - rings of tentacles surrounding their central mouth - adult body size: 2.0 – 200mm - (Dally et al. 2007) |
| <p>Anthozoa</p> | <p>Alcyonacea (soft coral)</p> |  <p>j.</p> | <p>SUSPENSION</p> | <ul style="list-style-type: none"> - endoskeleton - soft and often resemble plants or trees - non-reef-building corals - can grow wood-like cores and fleshy rinds for protection - adult body size: >200mm - (Dally et al., 2007) |
| | <p>Scleractinia (hard coral)</p> |  <p>k.</p> | <p>SUSPENSION</p> | <ul style="list-style-type: none"> - endoskeleton - hard and stony - primary reef-building corals - consist of hundreds to hundreds of thousands of individual polyps - polyps are cemented together by the calcium carbonate 'skeletons' they secrete - adult body size: 2.0 – 200mm - (Vaughan & Wells, 1943) |
| | <p>Echinoidea (sea urchin)</p> |  <p>l.</p> | <p>DEPOSIT</p> | <ul style="list-style-type: none"> - solid endoskeleton - round and spiny - planktotrophic larval and juvenile development - mobile epifauna <ul style="list-style-type: none"> - propel with tube feet and their spines - adult body size: 2.0 – 200mm - (Kroh, 2020) |
| <p>Ascidiacea</p> | <p>Stolidobranchia (tunicate)</p> |  <p>m.</p> | <p>SUSPENSION</p> | <ul style="list-style-type: none"> - soft bodied - filter feeders - rubbery or hard outer coat - two siphons to draw water into and out of the body - includes sea peaches and sea onions - (Monniot, 2001) |

Table 2.1 (4/4) Continued

| | | | | |
|--------------|---------------------------------|---|-------|--|
| Malacostraca | Decapoda (crab, hermit crab) |  n. | BOTH | <ul style="list-style-type: none"> - solid exoskeleton - five pairs of walking legs - adult body size: 2.0 – 200mm - (Poore, 2016) |
| | Euphausiacea (krill) |  o. | OTHER | <ul style="list-style-type: none"> - solid endoskeleton - shrimplike planktonic crustacean - (Martin & Davis 2001) |

Table 2.2 The calculated average abundance (individuals/m² or ind/m²) at BarC1-BarC10 for the three study years 2017, 2019 and 2021.

| AVERAGE of organism groupings | BarC1 | BarC2 | BarC3 | BarC4 | BarC5 | BarC6 | BarC7 | BarC8 | BarC9 | BarC10 |
|---|-------|-------|--------|--------|--------|--------|--------|--------|-------|--------|
| Valvatida (sun sea stars) | 0.26 | 0.06 | 0.12 | 0.19 | 0.10 | 0.71 | 0 | 0.07 | 0 | 0.06 |
| Phrynophiurida (basket stars) | 0 | 0.08 | 0.06 | 2.21 | 0.04 | 0 | 0 | 0 | 0 | 0 |
| Dendrochirotida (<i>psolus</i>) | 1.55 | 22.07 | 7.88 | 35.13 | 3.62 | 0.19 | 0 | 0 | 0.18 | 0 |
| Actiniaria (anemone) | 6.52 | 1.34 | 2.68 | 6.02 | 4.09 | 6.22 | 2.86 | 0.34 | 1.09 | 1.78 |
| Stolidobranchia (tunicate) | 2.90 | 0.87 | 0.07 | 0.16 | 0.27 | 0.10 | 0 | 0.08 | 0 | 0 |
| Scleractinia (hard coral) | 1.90 | 4.28 | 6.74 | 4.33 | 3.25 | 0.15 | 2.46 | 0.40 | 0.28 | 0.24 |
| Alcyonacea (soft coral) | 5.31 | 7.92 | 3.46 | 7.42 | 7.84 | 2.10 | 1.80 | 0.17 | 1.67 | 0.28 |
| Elasipodida (<i>O. glacialis</i>) | 0 | 0.26 | 595.96 | 1.05 | 1.48 | 0.20 | 0 | 0 | 0 | 0 |
| Decapoda (crab, hermit crab) | 2.08 | 0.78 | 1.55 | 2.91 | 1.11 | 1.28 | 0.29 | 0.09 | 0.11 | 0.17 |
| Nudibronchia (nudibranch) | 0 | 0 | 0 | 0.05 | 0 | 1.09 | 0.08 | 0 | 0 | 0 |
| Euphausiacea (krill) | 0.42 | 0.15 | 0.17 | 6.38 | 0.26 | 0.99 | 1.21 | 0.08 | 0 | 0.02 |
| Ophiuroidea (brittle star) | 0 | 0 | 1.71 | 40.42 | 293.97 | 671.91 | 450.71 | 258.03 | 49.50 | 20.08 |
| Astroidea (sea star) | 2.22 | 0.01 | 2.58 | 0.08 | 0.95 | 13.70 | 0.14 | 0.70 | 0.15 | 0.15 |
| Echinoidea (sea urchin) | 0.29 | 0.68 | 0.34 | 0.91 | 0.27 | 0.66 | 0.11 | 0 | 0 | 0 |
| Gastropoda (gastropod) | 0.53 | 0.15 | 0.21 | 0.49 | 0.69 | 1.028 | 0.20 | 0 | 0.10 | 0 |
| Total abundance | 23.97 | 38.65 | 623.53 | 107.75 | 317.95 | 700.32 | 459.85 | 259.96 | 53.08 | 22.78 |

Table 2.3 Summary table of the preliminary statistical analysis performed on the faunal abundance (ind/m²) data collected from the drop camera videos. Shown are the p-values and subsequent statistical results for twelve analysis of variance tests and two normality tests. Highlighted tests are ones shown to have statically significant results with a significance level of $\alpha=0.05$.

| Statistical test | p-value for the F-test and normality test | Conclusion |
|---------------------------------------|--|---|
| One-way Analysis of Variance | | |
| Northing | 1 | Fail to reject H ₀ No statistically significant differences |
| Overall abundance | 0.15 | Fail to reject H ₀ No statistically significant differences |
| Suspension Feeders | 0.35 | Fail to reject H ₀ No statistically significant differences |
| Deposit Feeders | 0.052 | Fail to reject H ₀ No statistically significant differences |
| Both Feeders | 0.16 | Fail to reject H ₀ No statistically significant differences |
| Ophiuroidea (brittle stars) | 0.59 | Fail to reject H ₀ No statistically significant differences |
| Elasipodida (<i>O. glacialis</i>) | 0.23 | Fail to reject H ₀ No statistically significant differences |
| Dendrochirotida (<i>psolus</i>) | 0.51 | Fail to reject H ₀ No statistically significant differences |
| Alcyonacea (soft coral) | 0.023 * | Reject H ₀ Statistically significantly variability |
| Actiniaria (anemone) | 0.41 | Fail to reject H ₀ No statistically significant differences |
| Gastropoda (gastropod) | 0.043 * | Reject H ₀ Statistically significantly variability |
| Decapoda (crab, hermit crab) | 0.016 * | Reject H ₀ Statistically significantly variability |
| Shapiro-Wilk normality test | | |
| Average abundance | 0.07 | Fail to reject H ₀ No evidence against normality |
| Ophiuroidea (brittle stars) abundance | 0.01 * | Reject H ₀ Population is NOT normally distributed around the trough of the Canyon |

Figures

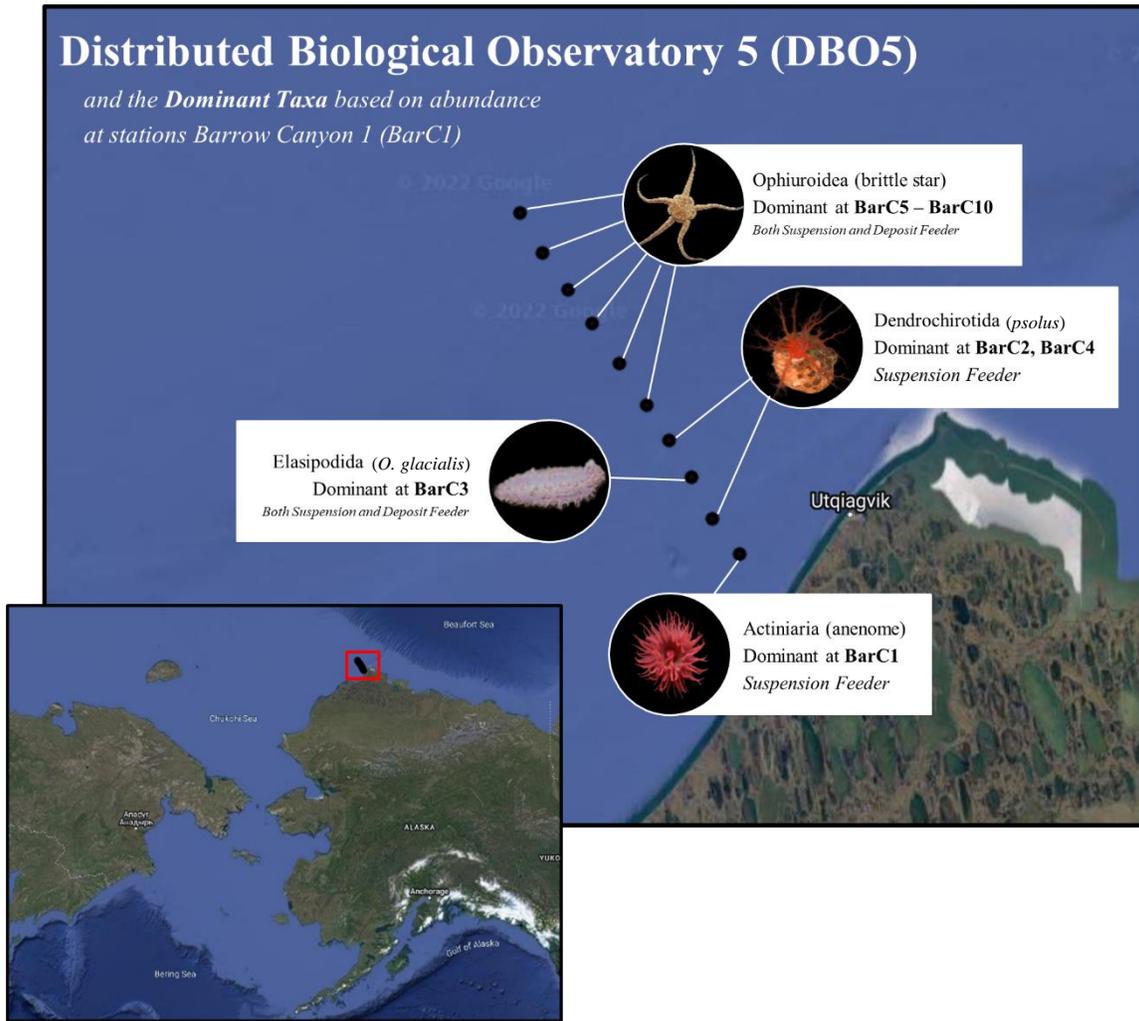


Figure 2.1 A map of the Distributed Biological Observatory 5 (DBO5) and surrounding region in the Northeastern Chukchi Sea which shows the location and dominant taxa of the ten stations that make up the cross-canyon sampling transect (BarC1- BarC10). Dominant taxa are based on abundance determined from the CCGS Sir Wilfrid Laurier July cruises in 2017, 2019 and 2021. Additional information of station depths and the regions bathymetry can be found in Table 1.1 and Figure 1.3, respectively. More information on the dominant taxa and references can be found in Table 2.1. Figure prepared using Google Earth Engine (<https://code.earthengine.google.com/>)

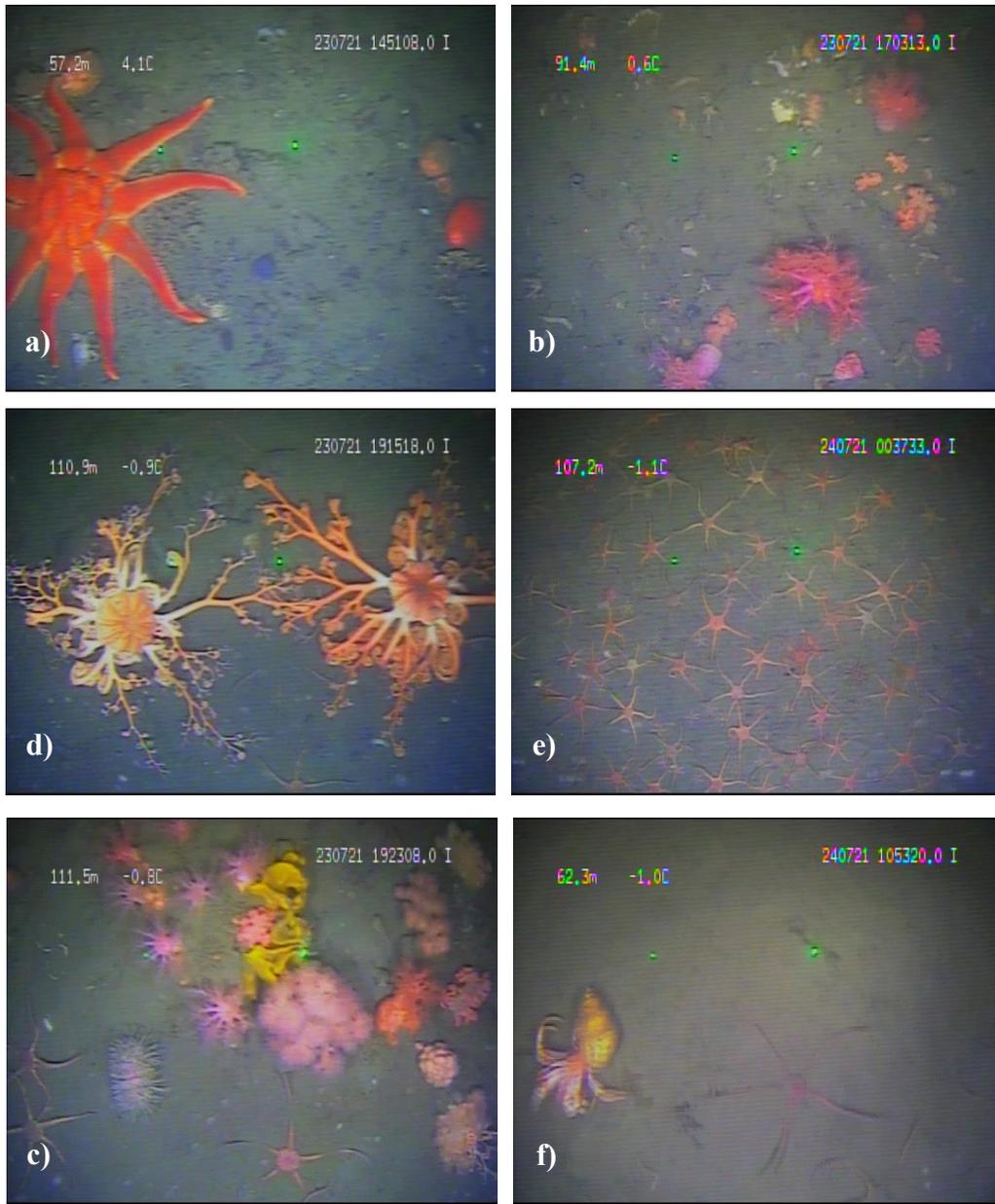


Figure 2.2 Examples of still image data exported from videos collected on the CCGS Sir Wilfrid Laurier July 2021 cruise. Each image is from the following respective stations: a) BarC2, b) BarC3, c) BarC4, d) BarC6, e) BarC4, f) BarC10. Note BarC=Barrow Canyon.

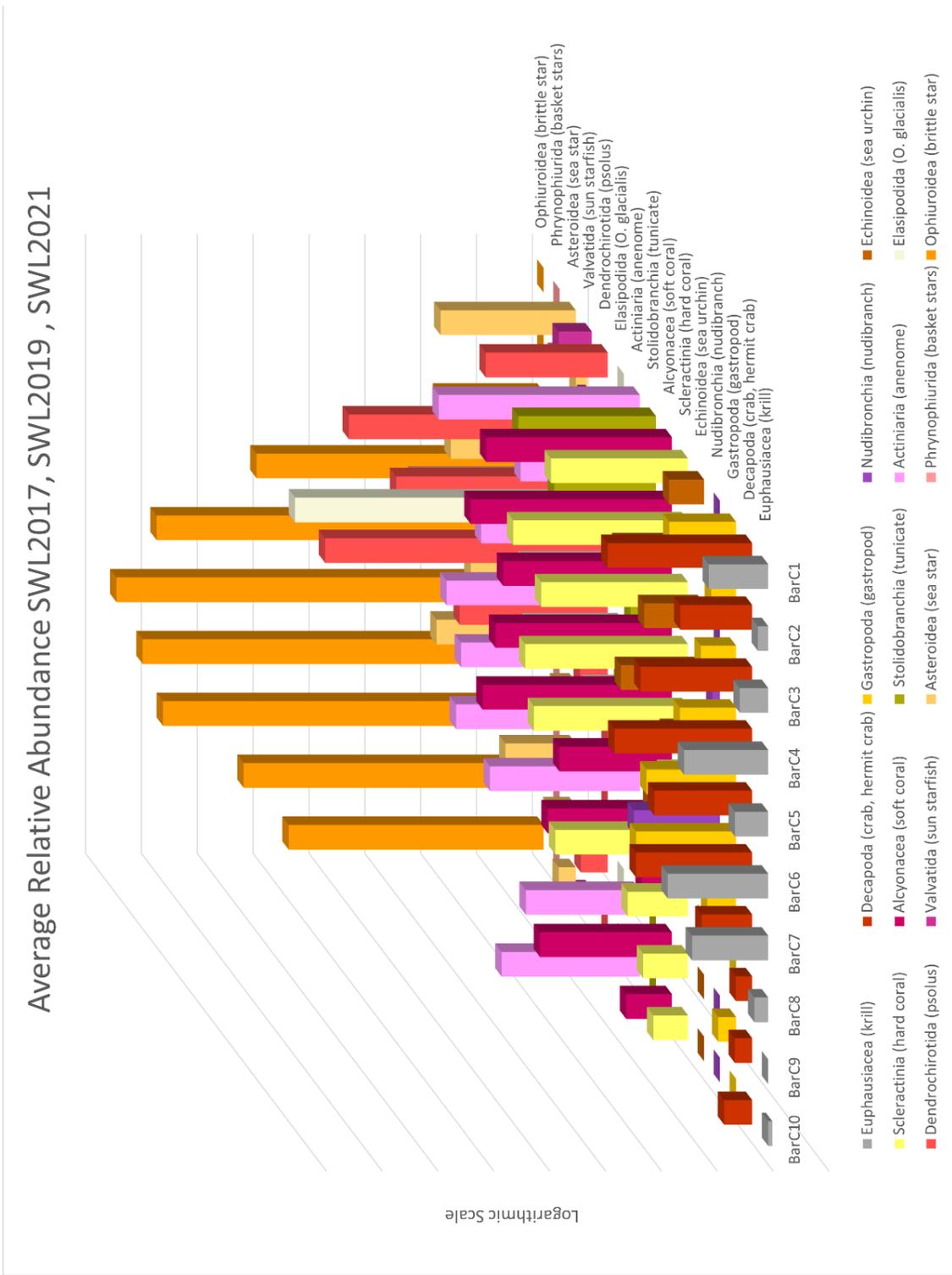


Figure 2.3 A bar graph showing the logarithmic relative abundance (ind/m²) of organisms across the DBO5 sampling stations (BarC1-BarC10). The x-axis indicates the station progression from west (BarC10) to east (BarC1) moving left to right along the axis.

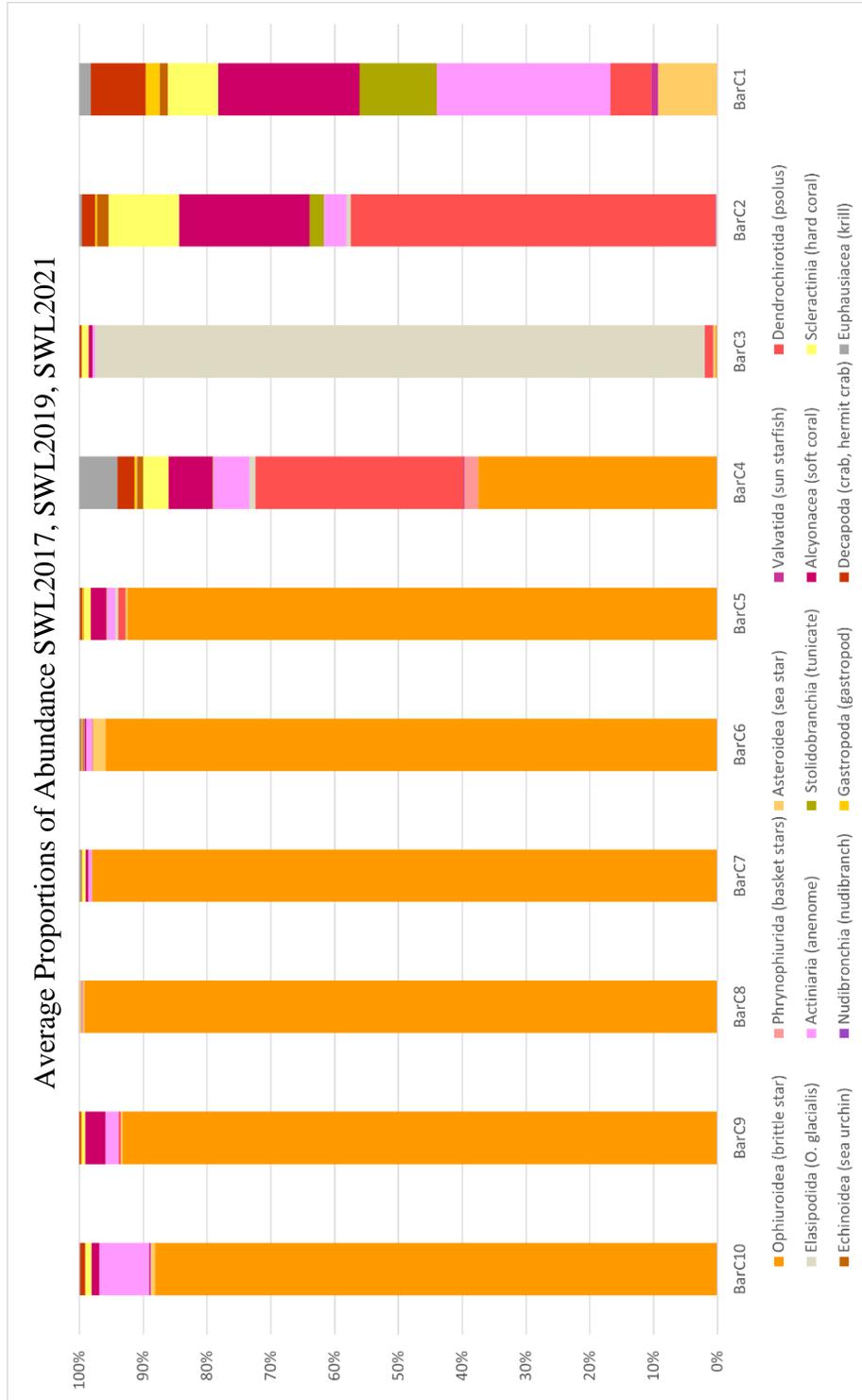


Figure 2.4 A bar graph showing the average proportion of abundance (ind/m²) across the DBO5 sampling stations (BarC1-BarC10). The x-axis shows the station progression from west (BarC10) to east (BarC1) moving left to right across the axis.

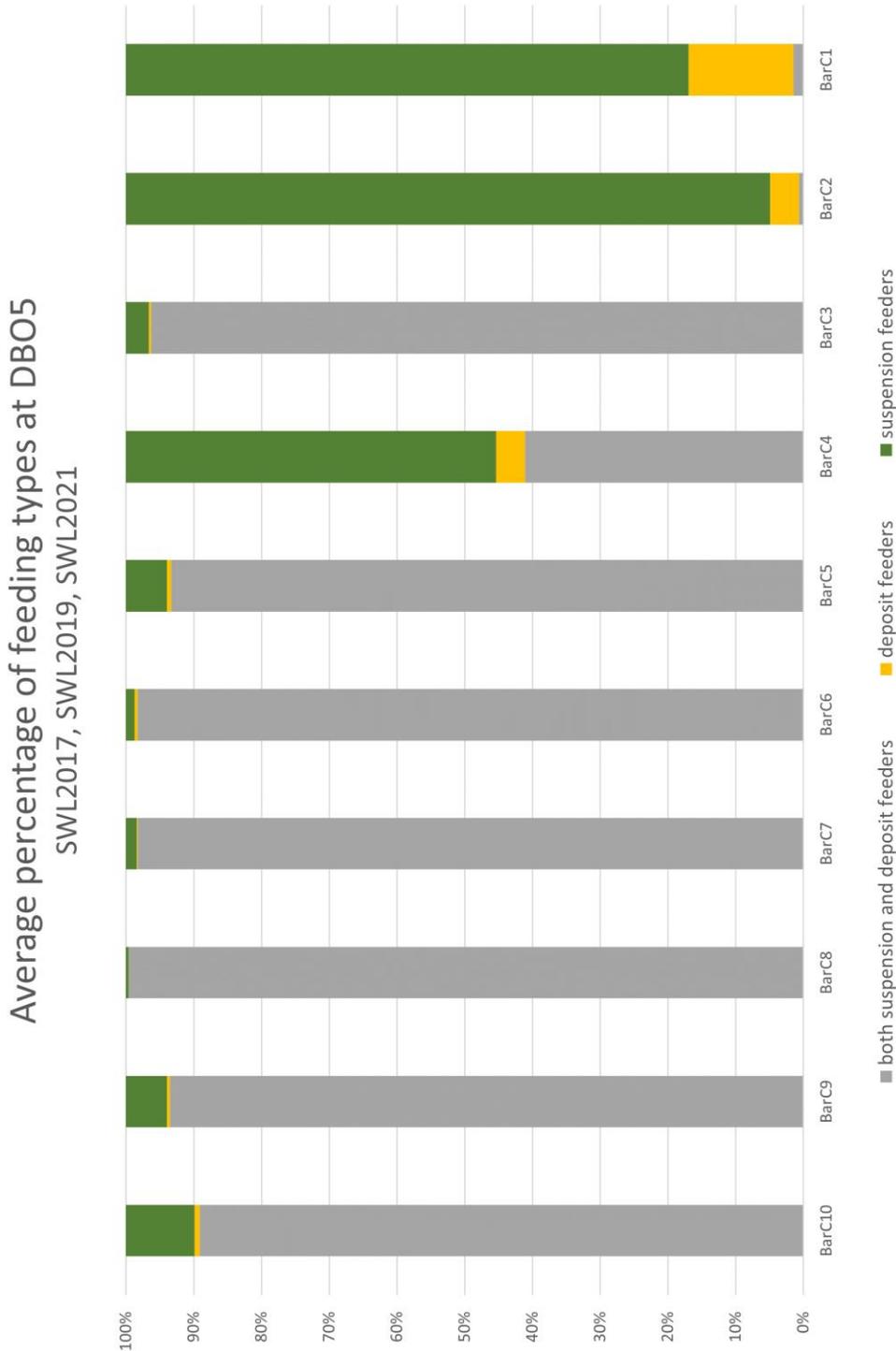


Figure 2.5 A bar graph showing the average proportion of individual faunal feeding type per m² across the DBO5 sampling stations (BarC1-BarC10). The x-axis shows the station progression from West (BarC10) to East (BarC1) moving left to right along the axis. Feeding types include deposit feeders, suspension feeders and organisms that can engage in both suspension or deposit feeding depending on environmental conditions.

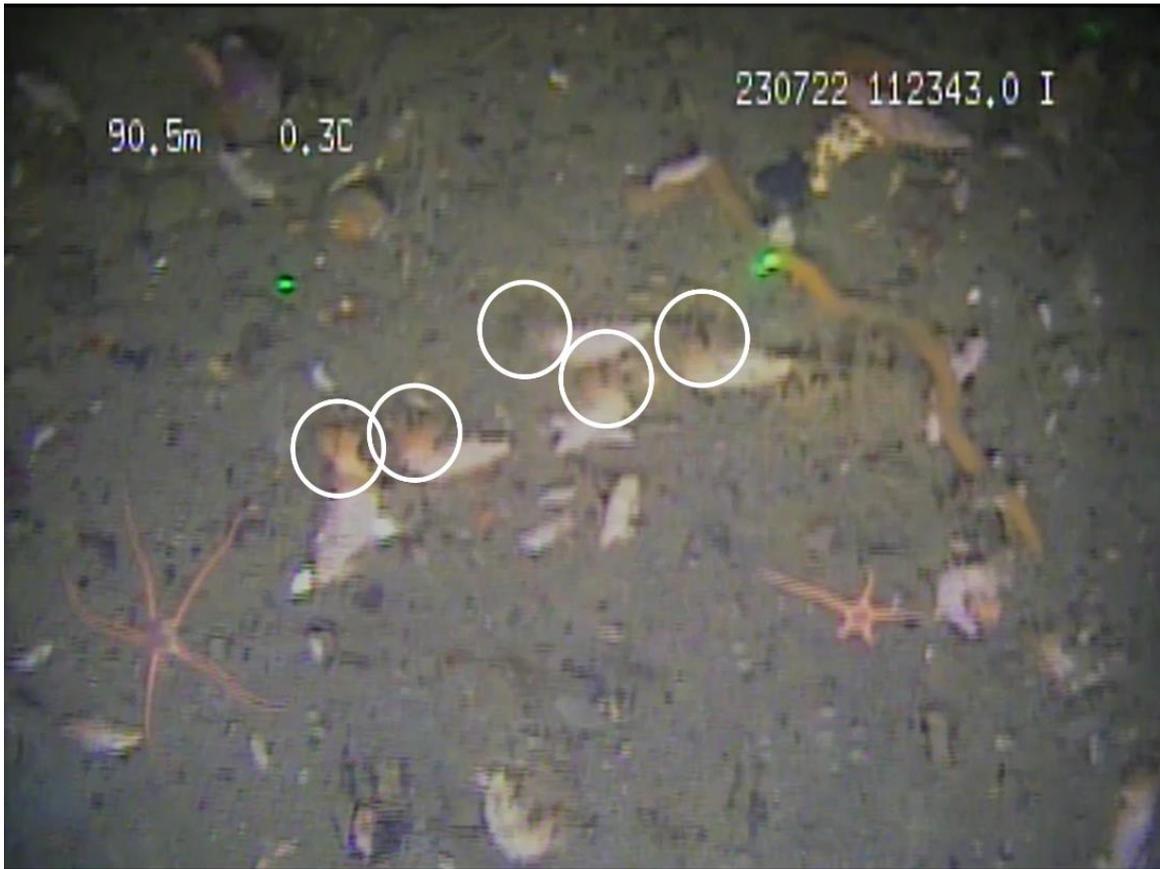


Figure 2.6 A still photo from BarC3 taken from the Canadian Coast Guard Vessel Sir Wilfrid Laurier 2022 video footage that shows extended tentacles on the sea cucumber *O. glacialis* circled in white. The tip of each tentacle contains papillae that secrete an adhesive material to capture particulate detritus to allow *O. glacialis* to suspension feed (Madsen & Hansen, 1994).

Appendix 1

The DCVS used aboard the CCGS Sir Wilfrid Laurier was manufactured by A.G.O. Environmental Electronics Ltd. in Victoria, B.C., Canada. Onboard the Drop Camera Video Suite are two positioning lasers 10cm apart, a thermometer, a pressure transducer for depth sensing and an undersea video camera (Figure A1.1). The instruments are situated within a metal frame and powered through a 200m electronic load-bearing cable attached to the top of the frame. The cable transmits a live video feed with an overlay of the date, time, depth and temperature to a shipboard desktop computer (Figure A1.2c). When prompted, the desktop computer records and saves clips of the live feed via VIDBOX® Video Conversion for Mac (www.vidbox.com) which is an off the shelf video (RCA inputs) to image file conversion software package. The shipboard arrangement also includes screen-sharing of the imagery captured to a second laptop computer at the ship rail, which enables the camera operator to control the quality of the imagery from the ship deck while it is deployed below.

To deploy the camera suite, the cable is situated in a snatch block fixed pulley system which extends over the side of the ship allowing the metal frame housing the camera to be lowered through the water column by hand (Figure A1.2a, b, d). While some testing of the camera used a machine-driven winch, a hand-powered winch deployment was found to afford sufficient control of the camera system at depth (Cooper et al. 2019). The ethernet connected Apple laptop computer is positioned on deck in a dark box next to the fixed pulley system so the operator of the camera can see the live feed and adjust the camera's proximity to the benthos in real time (Figure A1.2d). This helps to account for subtle changes in bathymetry, ship motion, and bottom water conditions. Once the camera is fully deployed, which varies depending on the station's local depth and current velocity, a recording is initiated via the VIDBOX® software. As a standard, assuming good video

quality, recordings at each station are for ten minutes. The average depth and temperature, start/stop time of the recording, local latitude and longitude, and qualitative observations of the live feed are noted during the recording for reference. The video files are saved as MP4 digital files via the MPEG-4 codec. File names include the sampling station as well as collection date and time for ease of post-cruise processing.

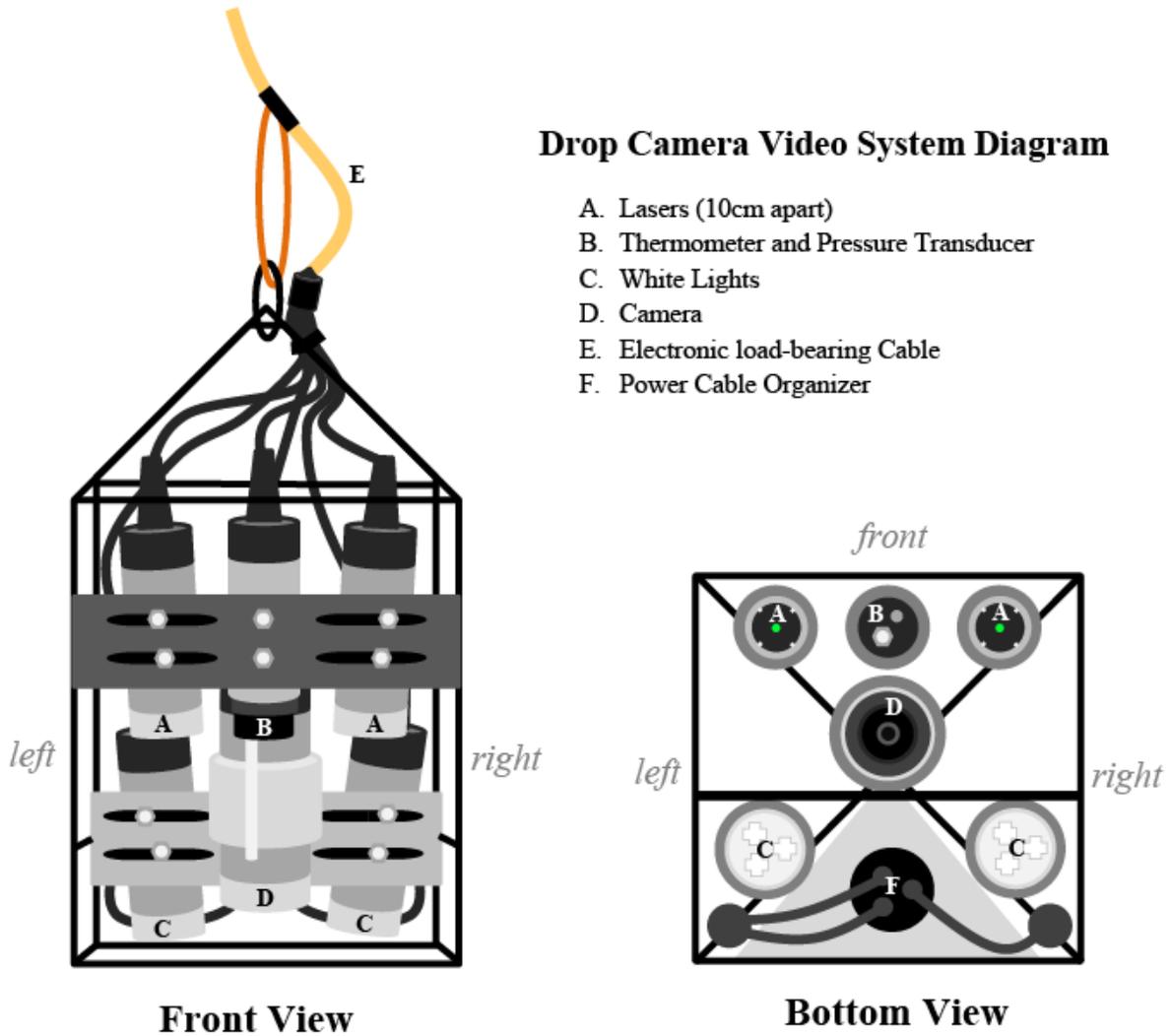


Figure A1.1 A diagram of the Drop Camera Video System which details the major components of the system including the lasers, lights, thermometer, pressure transducer for depth measurements and camera. This diagram also shows how power is supplied to the unit through an electronic load bearing cable and split power cables that supply different components individually.

Drop Camera Setup and Deployment

1. Camera System (for more detail see Figure A1.1)
2. Electronic load-bearing Cable (and reel)
3. Snatch Block (fixed pulley system)
4. Dark Box for Deck Laptop
5. Camera Operator's Stool
6. Desktop Monitor for Camera Operation

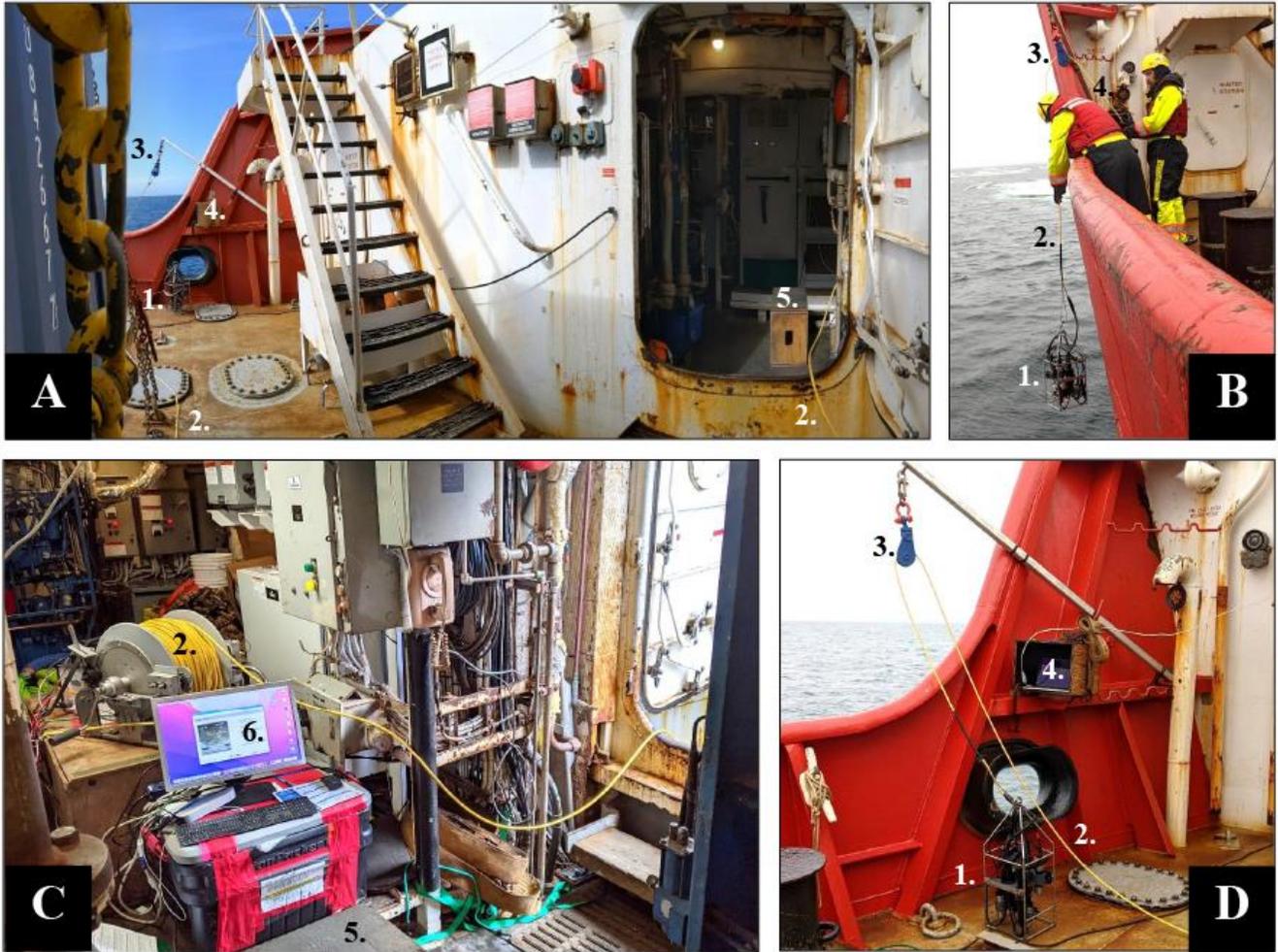


Figure A1.2 Images detailing the setup and deployment of the Drop Camera Video System aboard the CCGS Sir Wilfrid Laurier. A) is the view looking at both the indoor bay where the camera is operated from and the deck deployment area. B) shows camera system deployment using a snatch block fixed pulley system. C) is an image of the indoor bay where the camera is operated from on the desktop monitor, stored between stations and the electronic load bearing cable reel. D) shows the deployment setup including the snatch block fixed pulley system and the dark box for the live view laptop on deck.

Chapter 3: Drivers of Epibenthic Abundance and Diversity in the Barrow Canyon Region

1. Introduction

1.1 Understanding the importance of Abundance and Diversity in a changing Pacific Arctic

The Pacific Arctic is experiencing changes at an accelerating rate, so it is important to study the abundance of organisms as well as their diversity and composition on local to regional scales to understand how rapid changes are impacting the region's biology (Box et al., 2019; Grebmeier, 2012; Grebmeier et al., 2010; Hauser et al., 2018; Wood et al., 2015). Having a more accurate knowledge of abundance and diversity of benthic fauna will allow us to track population changes, identify coincident environmental drivers, and predict future changes to populations based on projected shifts in the environmental conditions. Faunal abundance, measured as individuals per m^2 (ind/ m^2), provides a general population indicator, while diversity, as defined by the Shannon-Weaver Diversity Index, looks at the relative abundance of organisms in an assemblage to account for both species' richness and evenness (Nolan & Callahan, 2006). Evaluating what promotes diversity specifically is necessary as diversity is not necessarily related to the abundance of individuals and yet is used as an indicator of ecosystem health (Lu et al., 2021). Diversity of benthic fauna is an important variable as faunal composition can alter the structure and composition of sediments, as well as its chemical properties, through activities such as feeding and burrowing. Thus, the diversity and types of epifauna and infauna can directly impact the environmental factors that promote ecosystem health (Graf & Rosenberg, 1997; Lu et al., 2021; Snelgrove, 1998). This is especially true on the Pacific Arctic shelves as they have significant benthic communities (Grebmeier et al., 2018). The shallow depths in tandem with high surface productivity and reduced seasonal zooplankton grazing, allow for a large export of labile carbon to the ocean floor where benthic biology plays a major role in material cycling and energy flow

throughout the whole Pacific Arctic system (Grebmeier et al., 2018). While benthic infauna and epifauna have been studied extensively in this region over the past several decades, there remains a need to expand our understanding of benthic populations, particularly of epifauna in regions where traditional epifaunal sampling techniques are challenging and limiting (Danielson et al., 2022; Grebmeier, 2012; Grebmeier et al., 2019; Rand et al., 2018). Trawling is a traditional oceanographic epibenthic sampling technique which allows for the study of abundance, diversity, size class and biomass in the Arctic (e.g. Danielson et al., 2022; Iken et al., 2019; Rand et al., 2018). However, trawling consumes significant and expensive ship sampling time, reduces our understanding of within station biological community composition, and it can have negative long-term effects on sampled regions, and is not possible in areas that have rocky benthos that would damage trawling equipment. This last drawback is particularly challenging as epibenthic communities vary greatly based on bottom composition. Therefore, the inability to sample all seafloors limits our knowledge of Pacific Arctic epibenthic biology.

1.2 Study Region and Drop Camera Video Sampling Technique

Barrow Canyon is a submarine Canyon located off Utqiagvik, Alaska, which starts on the Pacific Arctic Shelf and descends northward into the Canada Basin of the Arctic Ocean. This physical feature, which ranges from 50m to 3800m in depth from its southern head to its northern outlet, is an important channel where several shelf currents converge and exit the Chukchi Sea (Figure 1.1) (Stabeno et al., 2018). Currents in Barrow Canyon can be highly variable and dynamic in nature; but conditions can be divided into *Non-upwelling* and *Upwelling* (Figure 3.1) (Pickart et al., 2021). More often than not, conditions are Non-upwelling, in which there is a general northeastward flow from the Chukchi Sea shelf toward the Canada Basin, while Upwelling conditions are a reversal of this flow. The predominant Non-upwelling conditions funnel nutrients

and labile carbon from the highly productive shelf region to the Canyon where a vertical advection cell causes rapid downwelling of these materials to the benthos (Cooper et al., 2005; Hill & Cota, 2005; Pickart et al., 2021). This rapid downwelling supports a benthic biological hotspot that is incorporated into the Distributed Biological Observatory (DBO) and has been observed over time as a part of this international research effort and data sharing network (Grebmeier et al., 2019). These observations have been made along a transect of ten stations, DBO5, which crosses Barrow Canyon (BarC) with sampling locations denoted: BarC1-BarC10 (Figure 1.3). Because of variable and rapid currents present in Barrow Canyon, some parts of the Canyon contain very coarse-grained sediment and rocky benthic conditions (Figure 3.2). The combination of the depth, high current speeds, and coarse, rocky substrate make traditional epibenthic sampling techniques like trawling impractical. The combination of the importance of the benthic biology in Barrow Canyon as well as the inability to sample the epibenthos by traditional trawling, makes it a prime location to utilize alternative epibenthic sampling techniques, such as a Drop Camera Video System (DCVS).

A DCVS has been used aboard the Canadian Coast Guard Ship (CCGS) Sir Wilfrid Laurier for a number of years and has proven to be a cost-effective and versatile sampling technique in the Pacific Arctic Region (Cooper et al., 2019). The device described in this prior work is a hand-deployed instrument that is housed in a metal frame and powered through a 200m electronic load-bearing cable (Figure 2.7). Manually lowered through the water column via a snatch block fixed pulley system, the camera films the artificially illuminated benthos and transmits a live feed of video to a shipboard desktop computer where the footage can be watched in real time and recorded. This allows for a precursory rapid visual assessment of a station's epibenthic biological makeup, as well as producing a video file that can be used for abundance and diversity assessment, serving

as an original sample that can be continually referred to as it is unaltered by time or preservation methods (Bethoney & Stokesbury, 2018). This video sampling approach is cost effective at each stage from deployment to processing and storage (Clayton & Dennison, 2017). The DCVS is therefore an appropriate tool in the DBO epibenthic sampling regime, specifically in Barrow Canyon where other epibenthic sampling is impractical and benthic biology plays such a critical role in the ecosystem.

1.3 Environmental Drivers in the Barrow Canyon region

This study investigates several environmental factors as potential drivers of epibenthic abundance and diversity. Most of these variables are controlled by the two different water masses present in the Canyon which are Bering Sea Water (BSW) and Alaskan Coastal Water (ACW) carried in the Alaskan Coastal Current (ACC) (Figure 3.3) (Danielson et al., 2017, 2020; Dunbar, 1976; Gong & Pickart, 2015; Stabeno et al., 2018; Woodgate et al., 2005). The BSW impacts the offshore slope of the Canyon (BarC5-BarC10) and is cold, salty, nutrient-rich, and is present year-round. In contrast, the ACC is advected through the inshore slope of the Canyon and it is warmer, fresher, nutrient poor and only present seasonally (Pickart et al., 2021; Stabeno et al., 2018). These water masses influence water velocity, heat, salinity content, nutrients, particulate food and even benthic sediment grain size across the Canyon. To identify how these water masses and the environmental conditions they dictate impact the Canyon's epibenthic abundance and diversity, this study utilizes data collected shipboard on the water column temperature, salinity, absolute geostrophic velocity, chlorophyll a (chl a) content, bottom water inorganic macronutrients, chl a present in surface sediments, sediment grain size, total organic carbon (TOC) and total organic nitrogen (TON) at each sampling station. Depth is also considered as a potential environmental driver though of course it is not directly influenced by water mass.

1.4 Objective of Study

The objective of this study is to overcome challenges posed by traditional epibenthic sampling techniques while developing best-practices for utilizing a DCVS to evaluate abundance and diversity of epibenthic organisms in Barrow Canyon. The data sets that are developed will allow for an exploration of what environmental conditions control epibenthic community composition and provide insights as to why Barrow Canyon is a biological hotspot. This analysis will also allow future lines of inquiry into threats facing the abundance, diversity, and potentially overall health of this important boundary ecosystem between the Pacific Arctic and the Canada Basin of the Arctic Ocean (Figure 1.1). Therefore, by using a newer epibenthic sampling technique, we are expanding our ability to investigate the past, present, and future of the epibenthic community in an area that regulates two major Arctic regions.

1.5 Statement of Purpose and Hypotheses

The following statements are numbered to match their listing in Chapter 1 and listed again in Chapter 3.

3.1 What is the average epibenthic diversity of organisms at each station across Barrow Canyon (stations BarC1-BarC10)?

Hypotheses 3.1 Diversity varies between the inshore and offshore slopes of Barrow Canyon because the slopes are regulated by two different major shelf currents that converge in Barrow Canyon.

3.2 How does epibenthic diversity relate to other environmental variables across the Canyon?

Hypotheses 3.2 Diversity is positively correlated to absolute geostrophic velocity and temperature while negatively correlated to the percentage of fine grain particles in the sediment as well as salinity. Overall abundance of organisms is not correlated to the same environmental variables as diversity.

3.3 What are the most statistically significant drivers of epibenthic diversity in Barrow Canyon?

Hypotheses 3.3 The environmental drivers with the statistically significant correlation include absolute geostrophic velocity, sediment grain size, temperature, and salinity.

3.4 How could those drivers impact the future of the Canyon's epibenthic species composition?

Hypotheses 3.4 Any shift in the region's most significant environmental drivers of diversity could destabilize the higher richness and evenness of species that are currently present along the inshore slope of the Canyon.

2. Materials and Methods

2.1 Data Collection

Several data sets are used for this study which are outlined in Chapter 1 of this thesis (section 1.3)(Danielson et al., 2022). All data used, except for the ADCP derived velocity values, were collected aboard the CCGS Sir Wilfrid Laurier during the July occupation of the DBO5 line during 2017, 2019 and 2021, matching years of available video data. ADCP data are averages of Upwelling conditions and Non-upwelling conditions from 28 and 17 occupations, respectively, of the DBO5 line aboard several different vessels during July and August cruises (Pickart et al., 2021).

Brief descriptions of sampling equipment and the associated data sets produced that are used for our current analysis can be found in Appendix 2, while additional information on DCVS setup and deployment is found in Appendix 1.

2.2 Image Processing and Analysis

For three years of available data, 10 min consecutive video clips were collected at each of the ten stations that make up the cross-canyon DBO5 transect (BarC1-BarC10). To prepare the videos for analysis, footage files were imported in Adobe Premiere Pro video editor software (www.adobe.com/products/premiere.html) and stills exported in 10 second intervals in their original 720X480 aspect ratio. Preserving the image quality and pixel ratio increased accuracy of the area and abundance analysis, as well as the resulting diversity calculations. At 60 images per station, 10 stations per year, and 3 years, 300 minutes of video data were converted into 1800 images fit for further analysis (Figure 2.2).

Image analysis begins with counts of individuals present which included 15 groupings of organisms falling under eight taxonomic classes. Additional information on the organisms chosen for abundance analysis and parameters for counting partially in frame organisms can be found in chapter 2 of this thesis (Table 2.1). In addition to abundance, area analysis is conducted using two position lasers aboard the DCVS suite and Image Processing and Analyzing in Java or ImageJ/Fiji (<https://imagej.nih.gov/ij/>) which is an open-source, versatile image processing software hosted by the US National Institutes of Health. Using a ratio calculation with the known distance of 10 cm between the onboard lasers and the pixel aspect ratio, pixel distance is measured between the laser points in each frame and converted to area view in each still. More information on this calculation is provided in the methods section of Chapter 2.

Utilizing the sum abundance and sum area of the 60 images per station, ind/m² of epifauna are calculated for every station during the three sampling years. These numbers are calculated for the 15 organismal groupings as well as the 8 classes represented in these epifaunal organisms. This allows for inquiry into the abundance of specific organisms over time and in relation to environmental drivers as well as a diversity index calculation and an analysis of diversity to environmental driver correlations.

2.3 Statistical Analysis

In order to better understand the data produced from the methods described above, a series of statistical tests are performed to assess diversity, changes over time and statistically significant correlation between abundance, diversity, and choice environmental drivers. Using R, the Shannon-Weaver Diversity Indices (SWDI) are calculated for each DBO5 station during the 3 study years. Using these diversity Indices and the values for some of the environmental drivers listed in the introduction, one-way Analysis of Variance (ANOVA) tests with a significance level of $\alpha=0.05$ are performed on each variable to assess if there are any shifts in the diversity or environmental conditions that can be observed during our study period. The assumptions for the one-way ANOVA tests are 1) population normality, 2) sample independence and 3) homoscedasticity or the homogeneity of variance. The H_0 of the one-way ANOVA test is that there are no differences in the population means while the H_a is that there are differences in the population means.

Spearman's rank correlation coefficient tests with a significance level of $\alpha=0.05$ are performed between the overall station abundance, diversity, abundance of feeding groups discussed in Chapter 2 (suspension, deposit and organisms that can engage in both) and 14

potential environmental drivers: absolute geostrophic velocity of Non-upwelling conditions, range of absolute geostrophic velocity between Non-upwelling and Upwelling conditions, bottom water temperature, salinity, chlorophyll a, and nutrients (silicate, nitrate, phosphate and ammonia) as well as sediment chlorophyll a, grain size, total organic carbon (TOC) and total organic nitrogen (TON). This yields 70 potential correlations between population and environmental variables. Spearman correlations test for monotonic covariance between variables and assume ordinality of data. The p-values for these tests are adjusted using 1995 Benjamini & Hochberg method with test families being grouped by population variable. The p-values as well as the correlation coefficients will be listed to show statistical significance and the strength of the correlation.

3. Results

3.1 Abundance, Feeding Groups and Diversity

Abundance was measured as ind/m² and the results are displayed and discussed in Chapter 2 (Table 2.2, Figure 2.3). Overall trends include a peak in abundance with 700 ind/m² near the trough of the Canyon along the transect at BarC6 with a general bidirectional decrease in abundance towards BarC10 and BarC1. BarC3 was an exception from this trend as the abundance count in 2017 was very different from the counts in 2019 and 2021, with 1778 ind/m² during 2017, 33 ind/m² in 2019, and 59 ind/m² during 2021.

The abundance of different feeding groups was also measured as ind/m² (Chapter 2; Figure 2.5). Results show that organisms that are strictly suspension feeders are dominant at BarC1, BarC2 and BarC4 and their dominance is highest at BarC2, while organisms that are strictly deposit feeders are dominant at none of the stations but are most abundant at BarC1 (Figure 2.5). Organisms that can engage in both suspension and deposit feeding are the most dominant across

the Canyon specifically at BarC5-BarC10 and BarC3. The dominance at BarC5-BarC10 is associated with Ophiuroidea while the dominance at BarC3 is associated with Elaspodida (*O. glacialis*) (Table 2.2).

In order to explore the diversity across the Canyon and over the study period, SWDI were calculated and plotted using the eight taxonomic classes represented in the organisms enumerated across the Canyon (Table 3.1, Figure 3.4). There are limitations to studying diversity with video data as identification can only be made at higher taxonomic levels compared with the more laborious effort of microscope-based identifications. Using grabs or tow identification can often be made down to genus or species whereas video-based identifications are on the level of class or order. This causes an inherently lower observed diversity than if identifications were made down to genus or species. Acknowledging this limitation, I make comparisons only between diversity calculated at each station rather than comparing these SWDI to Indices calculated via other studies or collection methods.

The SWDI show that peak diversity is at station BarC1 during all three study years (SWDI of 1.59 in 2017, 1.73 in 2019 and 1.49 in 2021; Table 3.1, Figure 3.4). Lowest diversity across the Canyon is found at station BarC8, with SWDI of 0.01 in 2017 and 0.07 in both 2019 and 2021 (Table 3.1). A graph of SWDI shows that diversity generally increases bi-ordinally from station BarC8 eastward towards station BarC1 and westward towards BarC10; however, diversity is significantly higher at BarC1 than at BarC10 (Figure 3.4).

Similar to abundance, BarC3 appears to deviate from the trend of diversity across the Canyon. In 2017 when abundance at BarC3 was 1778 ind/m² in comparison with 33 ind/m² and 59 ind/m² both in 2019 and 2021, diversity is 0.08 in comparison with 0.89 and 1.22 during 2019

and 2021, respectively. Averages of abundance and diversity values at BarC3 excluding 2017, are in line with general increasing and decreasing trend across the Canyon for both variables. As previously mentioned, the organism that causes the dramatic increase in abundance at BarC3 is the sea cucumber *Elasipodida (O. glacialis)*, which is a member of the *Holothuroidea* class. The increase in *Elasipodida (O. glacialis)* causes a disproportionate increase in *Holothuroidea* at BarC3 in comparison with other taxonomic classes, therefore decreasing the overall diversity. Thus *Elasipodida (O. glacialis)* causes both the dramatic increase in abundance and decrease in diversity observed at BarC3 during 2017.

Looking at overall abundance in comparison to diversity, the results show that abundance peaks with a decrease up both slopes while diversity reaches a minimum with a steady bidirectional increase (Figure 3.5). However, the curves of abundance and diversity are not mirror images to each other because peak abundance is at BarC6 and the minimum diversity is at BarC8. This discontinuity is also observed at BarC1 and BarC10 where abundances are similar, but diversity values differ (Table 2.2, Table 3.1). Another visualization of abundance and the proportion of organismal abundance shows that while abundance generally increases near the trough of the Canyon, the inshore slope of the Canyon has higher diversity than the offshore slope of the Canyon (Figure 3.6)

3.2 Changes in Diversity and Environmental Conditions over the Study Period

One-way ANOVA tests were performed using data collected during the three study years to assess whether there were any statistically significant changes in diversity or environmental conditions during the six-year study period. Results of these variance analyses show that diversity did not significantly change during the study period ($p=0.75$; Table 3.2). The sole environmental

condition analyzed that had a statistically significant relationship with increasing diversity was bottom water silicate with a significance level of 0.0014 (Table 3.2).

3.3 Correlations between Epifaunal Abundance, Diversity, Feeding Groups and Environmental Conditions

To assess the significance of potential environmental drivers on epifaunal populations, Spearman-rank correlation coefficients for monotonic trends and p-values were calculated for 70 possible correlations among overall station epifaunal abundance, diversity, and abundance of feeding groups discussed in Chapter 2 (suspension, deposit and organisms that can engage in both feeding strategies) and 14 environmental variables. Among the environmental variables were the mean absolute geostrophic velocity of Non-upwelling conditions and the range of mean absolute geostrophic velocities between Upwelling and Non-upwelling conditions, hereafter referred to as the velocity variables. Non-upwelling is the term given to the predominant current condition where there is a strong transport of water offshore via the canyon while Upwelling refers to the reversal of that flow with the water flow moving back up the canyon towards the shelf (Figure 3.1). Of the 70 possible correlations analyzed, 48 were shown to be statistically significant with varying levels of significance. Correlations are considered significant if they have p-values <0.05 and highly significant if the p-value is <0.001 . Of the 48 significant correlations 20 were shown to be highly significant according to these parameters (Table 3.3).

The only environmental driver that is highly significantly correlated to overall abundance is depth with a regression coefficient of +0.71 and a significance level of $p = 0.0010$, meaning the highest abundance is found at the deepest depths sampled which averaged at 121 m. Of the 12 statistically significant environmental drivers correlated to diversity, 8 are highly significant

including bottom water (BW) temperature, salinity, nitrate as well as percentage fine particle sediment grain size, surface sediment TOC and TON content and the velocity variables. Bottom water temperature and the velocity variables are positively correlated to diversity while salinity, bottom water nitrate, percentage of fine particle sediment grain size, TOC and TON are negatively correlated. There are 11 significant correlations for the abundance of suspension feeders, with six that are highly significant: BW temperature and the velocity variables are positively correlated while BW silicate and nitrate as well as the percentage of fine particles in the surface sediment are negatively correlated. Deposit feeder abundance is correlated to eight environmental variables, with two positive highly significant correlations to the velocity variables. The abundance of epibenthic organisms that can suspension and deposit feed are correlated to all 14 of the examined environmental drivers; however, only 4 of those correlations are highly significant and each of those correlations had positive correlation coefficients. Those four are depth, bottom water salinity, bottom water ammonia, and percentage of sediment with fine grain size particles.

4. Discussion

4.1 Overview

The hypotheses posed in this study are well supported by the results. For example, in reference to question 3.1, which concerns the epibenthic diversity at each station across Barrow Canyon, the data suggest the epibenthic diversity is generally higher on the inshore slope of Barrow Canyon. This likely results from the seasonally present ACW, which is carried by the ACC and reflects higher summer temperatures, less saline conditions, and fewer nutrients (Figure 3.1, Figure 3.2, Figure 3.3). In contrast there is lower epibenthic diversity along the offshore slope of Barrow Canyon where the BSW moves more slowly, has colder temperatures, higher salinity and more

nutrients. This aligns with hypotheses 3.1 which suggests that the diversity may be regulated by the two shelf currents that converge in Barrow Canyon. This is also further supported by data that relate to the environmental variables that are correlated to epibenthic diversity (question 3.2) and which of those variables are the most statistically significant drivers of diversity (question 3.3). While the list of environmental conditions examined as a part of this study is by no means exhaustive, the variables investigated cover a wide range of physical and chemical properties of the benthic environment. All but one of these variables vary with the two major water masses moving through Barrow Canyon: the inshore ACW and offshore BSW. Depth is the only environmental variable assessed that cannot be related to the water mass types in the Canyon and it is one of the few that is not correlated to diversity. Conversely, some of the variables most strongly correlated to diversity are velocity, BW temperature, BW salinity, and sediment grain size which are dictated by the prevailing water mass at each station. While statistical correlation is not evidence enough to indicate specifically which, if any of these environmental conditions promotes diversity, it does suggest that the ACW brought to the Canyon within the ACC promotes a more diverse epibenthic population assemblage. This is likely via the ACC impact on sediment grain size with faster currents creating coarser sediment benthos as well as the lower annual productivity in ACW due to low seasonal nutrients. In contrast, this is not true for overall abundance (hypotheses 3.2). The only environmental variable that is strongly correlated with abundance is depth, which again is also the only environmental variable measured that is not affected by water mass. Therefore, while abundance appears to not be directly correlated to currents and water masses, epibenthic diversity is very closely related to the factors that the two separate water masses influence. This leads to question 3.4, specifically how the environmental drivers identified could impact the future evenness and richness of species in the Canyon. As discussed in chapter 1, while

it is understood that warming seas and melting sea ice are impacting the Arctic Ocean's circulation, it is unclear what those changes will be and on what timescales they will occur (Armitage et al., 2020; Timmermans & Marshall, 2020). Therefore, because the results of this study suggest that water masses and currents impact epibenthic diversity through variables such as sediment grain size and food supply, it follows that changes in the currents impacting the distribution of different water masses may also affect the diversity observed across the Canyon. For example, if the currents transporting water offshore via Barrow Canyon slow, finer grain size sediment will become more predominant along each slope. This will decrease the abundance of obligate suspension feeders, particularly along the inshore slope of the Canyon where their present populations are supported by faster currents and coarser sediments. This will lower the functional and possibly taxonomic diversity across the Canyon. While such changes are possible in the future, it is not practical given current knowledge to predict the exact timescale or nature of impacts to epibenthic diversity.

Also of interest is the significant variation of silicate during the study period as shown by the one-way ANOVA performed on the mean values for the silicate along the DBO5 transect. Higher BW silicate is an indicator of Anadyr and Bering Shelf water, meaning that its variation during the study period could suggest changes in the movement or presence of the BSW along the Barrow Canyon transect. This warrants further exploration into how silicate values are fluctuating across DBO5 and what that may tell us about how the location of BSW in the Canyon may change from one sampling to another.

4.2 Abundance Trends and Drivers and Outliers

The data show that abundance is normally distributed across the Canyon and strongly correlated to depth. More detail on specific trends observed in abundance data are presented

elsewhere (chapter 2) while the data presented in this chapter builds upon that understanding by showing a strong positive significant correlation between depth and abundance (Table 3.3). Other studies have also observed correlations between depth and organisms along the DBO5 transect with the infauna biomass peaking at BarC5 (Grebmeier & Cooper, 2020; Pickart et al., 2021) (Figure 3.7). Pickart et al. (2021) suggests that this pattern results from the interaction of currents in the Canyon, creating rapid downwelling of labile organic carbon directly to the deeper parts of the Canyon. The primary source of food for benthic organisms in Barrow Canyon come from phytoplankton blooms observed to the west of the DBO5 transect line in the vicinity of Hanna Shoal (Figure 3.3d). This labile organic carbon is transported via the BSW to the Canyon where the BSW interacts with the ACC above the downward slope of Barrow Canyon's central channel (Figure 3.3 a,b). The interaction of the currents creates a rapid downwelling of food supply to the trough of the Canyon via an advection cell on the cyclonic side of the northward flow (Figure 3.3b). This can be observed through a vertical section of the fluorescing material along the DBO5 transect (Figure 3.3c). Pickart et al. (2021) concluded that this transport of food supply directly to the Canyon's base facilitates the maintenance of the high macrofaunal biomass observed there. While abundance of epifauna cannot be directly related to biomass of infauna, it is possible that this downwelling of organic matters is also responsible for the abundance trends described above. Therefore, while depth is the variable that is most strongly correlated to epifaunal abundance, and is itself not directly impacted by currents, it is possible that the currents are still primary drivers of abundance by the way they transport food to the central channel of the Canyon. This suggests that food availability supplied by current transport and interactions plays a role in where the highest epibenthic abundance can be found.

Across the data and analysis presented in both Chapter 2 and Chapter 3 of this thesis, BarC3 is an outlier station that does not align with the overall trends in abundance or diversity observed across the Canyon (Figure 3.5). As previously described, a peak in the presence of *Elasipodida (O. glacialis)* in 2017 skews the average epifaunal abundance to be markedly higher, and epifaunal diversity to be markedly lower than during the two other study years. Because this phenomenon was only observed during one of three study years analyzed in this thesis, there are not sufficient data to fully examine or to reach conclusions about the causes of the abundance spike. While acknowledging the limitations of the available data, I provide a preliminary analysis to inform future lines of inquiry. The abundance of *Elasipodida (O. glacialis)* does not appear to be significantly correlated to any environmental variable that could be expected to fluctuate over the study period including bottom water temperature, salinity, or chl a in the bottom water and sediments, as well as bottom water nutrient concentrations (Table 3.4). There is a significant correlation to bottom water nitrate with a p-value of 0.01; however, as the analysis of variance shows, there is no statistically significant change in the mean bottom water nitrate concentrations over the study period along the DBO5 transect (Table 3.4). Therefore, these limited data suggest that there is no fluctuation in environmental conditions that is directly responsible for the spike in *Elasipodida (O. glacialis)* abundance during 2017. However, using abundance data from infauna grabs dating back to 2007, an expanded graph of *Elasipodida (O. glacialis)* abundance, indicates that 2017 is not the only year when a sharp rise in abundance occurred (Figure 3.8). While this data set is again limited due to the comparison between abundance data via infauna grabs and epifauna videos, there is a cyclic trend of abundance that appears to occur over a 7- or 8-year period. The two possibly observed complete cycles appear to begin in 2007 and 2013 with a third cycle beginning in 2020 or 2021 (Figure 3.8). The peaks in abundance were >1000 ind/m² while

nonpeak years have between 10 and 100 ind/m². Additional data and standardization of data are necessary to draw conclusions to what appears to be a population cycle.

4.3 Feeding group Trends and Drivers

The distribution of abundance by feeding group is discussed elsewhere (chapter 2), while the data presented in this chapter establishes correlations and potential drivers that cause the difference in distribution between suspension and deposit feeders as well as organisms that can engage in either suspension or deposit feeding. These data suggest that suspension feeders and benthic organisms that can both suspension and deposit feed, are the two most predominant feeding types in the Canyon and strict deposit feeders are less prevalent.

While BarC1, 2 and 4 are benthic habitats dominated by suspension feeders, BarC3 is predominantly Elaspodida, which can both suspension and deposit feed. However, video data suggests that Elaspodida are suspension feeding at BarC3 (Figure 2.6), meaning the entire section of inshore slope sampled along the DBO5 line supports suspension feeders. This is further supported by the strong statistically significant correlations between strictly suspension feeders and the environmental conditions that are associated with the inshore ACW. Suspension feeders are highly correlated with warmer temperatures, faster currents, more current variability, lower bottom water nutrients, and coarser sediments (Table 3.3). This aligns with the feeding strategy that suspension feeders use by affixing themselves to the benthos rather than burrowing and use the larger grain substrate for the benthic stability it provides (Sebens et al., 2017; Krumbein, 1934). The faster currents that contribute to the presence of coarse sediments (as discussed in chapter 1), also benefit suspension feeders by continuously bringing a supply of suspended food sources to the inshore slope. This explains why the high absolute geostrophic velocity typical of Non-

upwelling conditions as well as the variability between mean velocity during Non-upwelling and Upwelling conditions are strongly correlated to suspension feeder abundance.

In contrast, in all years, the stations at BarC5-10 have the highest abundance of organisms that can suspension and deposit feed, which is the result of high abundance of Ophiuroidea (brittle star) at each of these stations. The water mass impacting the offshore slope is BSW and just as BSW contrasts with ACW in that it is slower, colder, more nutrient rich, and has a higher salinity content, so do the coefficient of correlation vary between organisms that can suspension and deposit feed, and obligate suspension feeders. Organisms that can both suspension and deposit feed are negatively correlated with temperature (i.e. colder temperatures = high abundance) and positively correlated with bottom water salinity, percentage of fine grain size sediment and bottom water nutrient concentrations (Table 3.3). This is consistent with the versatility of Ophiuroidea (brittle star) feeding mechanisms being well suited to an environment with finer sediments and particle settling where deposit feeding is possible, as well as sufficient variability due to changing velocity conditions to make suspension feeding a beneficial trait (Hansson, 2001). Therefore, the dichotomous nature of the inshore water mass versus the offshore water mass is reflected in not only the environmental conditions but also in the feeding types present in both locations.

4.4 Diversity Trends and Diversity

Diversity is not uniformly distributed across the Canyon, with higher diversity of organisms along the inshore slope and higher correlations between diversity and environmental conditions associated with the ACW. As with strictly suspension feeders, diversity is positively correlated with bottom water temperature and negatively correlated with bottom water salinity, fine grain size sediment and bottom water nutrient concentrations (Table 3.3). This would suggest that

that ACW promotes a more diverse epibenthic regime as opposed to BSW, which supports less diversity. This pattern fits with the assumption that more variability in a system (higher variability of currents and resulting food and nutrient supply, etc.) leads to more diversity as organisms occupy a variety of niches present (Levine & HilleRisLambers, 2009). While the percentage of fine grain size substrate is a single quantitative measurement useful for statistical analysis, it does not encapsulate the true variability of the inshore benthos that is in part due the higher velocity of currents that occur there (Grebmeier & McRoy, 1989; Reynolds, 1883). As discussed in chapter 2, one of the strengths of video data is the ability to better understand in situ conditions including the variability of benthic environment within a single station. Videos taken at BarC1-BarC4 show that not only do the inshore stations have coarser sediments, but there are also intermittent larger rocks that interrupt sediment distributions (Figure 3.9). These rocks contribute to biodiversity as some organisms colonize and cluster on the rocks while others are more evenly spread on other benthic substrate. These factors contribute to the higher diversity inshore and mean that, via their effect on sediment grain size, currents and velocity indirectly impact the diversity of organisms. This suggests again that different water masses that affect the inshore slope (ACW) vs the offshore slope (BSW) control not only environmental conditions and feeding type distributions but also diversity.

5. Conclusions and Future Work

The data presented here suggest that water masses and currents play a major role in controlling abundance, diversity, and distribution of epifaunal feeding groups in Barrow Canyon. Epifaunal abundance is most strongly positively correlated to depth, and while depth is not influenced by currents, the interaction of currents above the deepest channel of Barrow Canyon is what creates rapid downwelling of food sources to the trough of the Canyon. This suggests

that currents are indirectly responsible for high abundance of epifauna at the base of this transect across the Canyon (Cooper et al., 2005; Hill & Cota, 2005; Pickart et al., 2021). While not directly comparable, similar results in the peak infauna biomass at the base of the DBO5 transect across the Canyon is consistent with rapid transport of labile organic carbon to the trough of the Canyon, that supports a hotspot for benthic fauna (Grebmeier & Cooper, 2020; Pickart et al., 2021). Epifaunal diversity appears to be more directly related to water mass types and currents as higher SWDI is associated with the physical and chemical characteristics of the inshore ACW while lower SWDI is correlated to the physical and chemical characteristics of the offshore BSW. This is also true of feeding group distribution with predominantly suspension feeders in the faster moving ACC along the inshore slope while the offshore slope is dominated by organisms that have versatile feeding strategies with the ability to engage in both deposit and suspension feeding. Suspension feeders are favored where suspended particulate food is continuously supplied via the stronger absolute geostrophic velocity of the modal Non-upwelling conditions as well as a larger range of velocity between Non-upwelling and Upwelling conditions. In contrast, the versatility of feeding strategies of organisms aligns with the partially deposited, partially suspended nature of particulate matter that is associated with the slower moving BSW. Therefore, the currents that converge in Barrow Canyon are not only responsible for the dichotomous nature of the physical and chemical regimes along the inshore and offshore slopes, but also the differences in diversity and feeding groups between the two and even the peak in abundance at the trough of the Canyon. This makes the abundance and distribution of epibenthic species in the Canyon a function in part of currents and thus susceptible to destabilization and reorganization if currents were to shift in the future.

This study provides a foundation for additional DCVS data collection that would create a longer epibenthic diversity time series in the Canyon region. Tracking changes in diversity along with the already studied changes in environmental conditions such as sea ice retreat and current shifts, will allow for further understanding of the relationship between epibenthic diversity and water masses as well as how changes in environmental conditions may impact the epibenthos. In addition to a temporal expansion of data, a spatial expansion of analysis to other regional observations within the DBO network will allow for a greater understanding of epibenthic abundance and diversity across the Pacific Arctic Region. While the DCVS is particularly powerful in Barrow Canyon where trawling is challenging and the epibenthic fauna varies greatly across a small area, other strengths of the DCVS also apply to other DBOs: in-situ visualization, understanding within station distribution of epibenthic species, and the cost-effective nature of collection processing and storage. Finally, an as yet untapped strength of the DCVS video data, is the opportunity for size class analysis of epibenthic populations using the positioning lasers and software such as ImageJ. This could offer a new means of determining the age, health, and longevity of epibenthic populations, at a lower cost than equivalent approaches using trawling data. This thesis shows the capability of DCVS approaches to inform our understanding of environmental drivers control on epibenthic populations. In addition, the approach has enormous potential to advance our temporal, spatial and more in depth understanding of the epibenthic system in the Pacific Arctic region.

References

- Amante, C., & Eakins, B. W. (2009). NOAA Technical Memorandum NESDIS NGDC-24 ETOPO1 1 ARC-minute global relief model: procedures, data sources and analysis. <https://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/docs/ETOPO1.pdf>
- Armitage, T. W. K., Manucharyan, G. E., Petty, A. A., Kwok, R., & Thompson, A. F. (2020). Enhanced eddy activity in the Beaufort Gyre in response to sea ice loss. *Nature Communications*, *11*(1). <https://doi.org/10.1038/s41467-020-14449-z>
- Bethoney, N. D., & Stokesbury, K. D. E. (2018). Methods for image-based surveys of benthic macroinvertebrates and their habitat exemplified by the drop camera survey for the Atlantic Sea Scallop. *Journal of Visualized Experiments*, *137*. <https://doi.org/10.3791/57493>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F. J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., & Olsen, M. S. (2019). Key indicators of Arctic climate change: 1971-2017. *Environmental Research Letters*, *14*(4). Institute of Physics Publishing. <https://doi.org/10.1088/1748-9326/aafc1b>
- Clayton, L., & Dennison, G. (2017). Inexpensive video drop-camera for surveying sensitive benthic habitats: applications from glass sponge (Hexactinellida) reefs in Howe Sound, British Columbia. *The Canadian Field-Naturalist*, *131*(1), 46–54. <https://doi.org/10.22621/cfn.v131i1.1783>
- Coachman, L. K., Aagaard, K., & Tripp, R. B. (1975). Bering Strait: The regional physical oceanography. University of Washington Press.
- Cooper, L. W., Guarinello, M. L., Grebmeier, J. M., Bayard, A., Lovvorn, J. R., North, C. A., & Kolts, J. M. (2019). A video seafloor survey of epibenthic communities in the Pacific Arctic including Distributed Biological Observatory stations in the northern Bering and Chukchi seas. *Deep Sea Research Part II: Topical Studies in Oceanography*, *162*, 164–179. <https://doi.org/10.1016/j.dsr2.2019.05.003>
- Cooper, L. W., Larsen, I. L., Grebmeier, J. M., & Moran, S. B. (2005). Detection of rapid deposition of sea ice-rafted material to the Arctic Ocean benthos using the cosmogenic tracer ^7Be . *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(24–26), 3452–3461. <https://doi.org/10.1016/j.dsr2.2005.10.011>
- Danielson, S. L., Eisner, L., Ladd, C., Mordy, C., Sousa, L., & Weingartner, T. J. (2017). A comparison between late summer 2012 and 2013 water masses, macronutrients, and phytoplankton standing crops in the northern Bering and Chukchi Seas. *Deep Sea Research*

Part II: Topical Studies in Oceanography, 135, 7–26.
<https://doi.org/10.1016/j.dsr2.2016.05.024>

- Danielson, S. L., Grebmeier, J. M., Iken, K., Berchok, C., Britt, L., Dunton, K., Eisner, L., Farley, E., Fujiwara, A., Hauser, D., Itoh, M., Kikuchi, T., Kotwicki, S., Kuletz, K., Mordy, C., Nishino, S., Peralta-Ferriz, C., Pickart, R., Stabeno, P. J., ... Woodgate, R. A. (2022). Monitoring Alaskan Arctic Shelf ecosystems through collaborative observation networks. *Oceanography*. <https://doi.org/10.5670/oceanog.2022.119>
- Danielson, S. L., Hennon, T. D., Hedstrom, K. S., Pnyushkov, A., Polyakov, I., Carmack, E., Filchuk, K., Janout, M., Makhotin, M., Williams, W. J., & Padman, L. (2020). Oceanic routing of wind-sourced energy along the Arctic continental shelves. *Frontiers in Marine Science*, 7. <https://doi.org/10.3389/fmars.2020.00509>
- Gong, D., & Pickart, R. S. (2015). Summertime circulation in the eastern Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 118, 18–31. <https://doi.org/10.1016/j.dsr2.2015.02.006>
- Graf, G., & Rosenberg, R. (1997). Bioresuspension and biodeposition: a review. *Journal of Marine Systems*, 11(3–4), 269–278. [https://doi.org/10.1016/S0924-7963\(96\)00126-1](https://doi.org/10.1016/S0924-7963(96)00126-1)
- Grebmeier, J. M. (2012). Shifting patterns of life in the Pacific Arctic and sub-Arctic Seas. *Annual Review of Marine Science*, 4, 63–78. <https://doi.org/10.1146/annurev-marine-120710-100926>
- Grebmeier, J. M., & Cooper, L. W. (2020). Benthic macroinfaunal and dominant taxa samples collected from Northern Bering Sea to Chukchi Sea, 1970–2017. In *Arctic Data Center*. <https://doi.org/10.18739/A2SX6499X>.
- Grebmeier, J. M., Frey, K., Cooper, L., & Kędra, M. (2018). Trends in benthic macrofaunal populations, seasonal sea ice persistence, and bottom water temperatures in the Bering Strait region. *Oceanography*, 31(2). <https://doi.org/10.5670/oceanog.2018.224>
- Grebmeier, J. M., & McRoy, P. C. (1989). Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. III. Benthic food supply and carbon cycling. *Marine Ecology Progress Series*, 53(1), 79–91. <http://www.jstor.org/stable/24834380>
- Grebmeier, J. M., Moore, S. E., Cooper, L. W., & Frey, K. E. (2019). The Distributed Biological Observatory: A change detection array in the Pacific Arctic – An introduction. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 1–7. <https://doi.org/10.1016/j.dsr2.2019.05.005>

- Grebmeier, J. M., Moore, S. E., Overland, J. E., Frey, K. E., & Gradinger, R. (2010). Biological response to recent Pacific Arctic sea ice retreats. *Eos, Transactions American Geophysical Union*, 91(18), 161. <https://doi.org/10.1029/2010EO180001>
- Hansson, H. G. (2001). Echinodermata. In M. J. Costello, C. Emblow, & R. J. White (Eds.), *European register of marine species: a check-list of the marine species in Europe and a bibliography of guides to their identification* (Vol. 50, pp. 336–351). Collection Patrimoines Naturels.
- Hauser, D. D. W., Laidre, K. L., Stern, H. L., Suydam, R. S., & Richard, P. R. (2018). Indirect effects of sea ice loss on summer-fall habitat and behaviour for sympatric populations of an Arctic marine predator. *Diversity and Distributions*, 24(6), 791–799. <https://doi.org/10.1111/ddi.12722>
- Hill, V., & Cota, G. (2005). Spatial patterns of primary production on the shelf, slope and basin of the Western Arctic in 2002. *Deep Sea Research Part II: Topical Studies in Oceanography*, 52(24–26), 3344–3354. <https://doi.org/10.1016/j.dsr2.2005.10.001>
- Iken, K., Mueter, F., Grebmeier, J. M., Cooper, L. W., Danielson, S. L., & Bluhm, B. A. (2019). Developing an observational design for epibenthos and fish assemblages in the Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 180–190. <https://doi.org/10.1016/j.dsr2.2018.11.005>
- Krumbein, W. C. (1934). Size frequency distributions of sediments. *SEPM Journal of Sedimentary Research*, Vol. 4. <https://doi.org/10.1306/D4268EB9-2B26-11D7-8648000102C1865D>
- Levine, J. M., & HilleRisLambers, J. (2009). The importance of niches for the maintenance of species diversity. *Nature*, 461(7261), 254–257. <https://doi.org/10.1038/nature08251>
- Lu, X., Xu, J., Xu, Z., & Liu, X. (2021). Assessment of benthic ecological quality status using multi-biotic indices based on macrofaunal assemblages in a semi-enclosed bay. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.734710>
- Nolan, K. A., & Callahan, J. E. (2006). Beachcomber biology: The Shannon-Weiner species diversity index. *Tested Studies for Laboratory Teaching*, 27, 334–338. https://www.ableweb.org/biologylabs/wp-content/uploads/volumes/vol-27/22_Nolan.pdf
- Pickart, R. S., Spall, M. A., Lin, P., Bahr, F., McRaven, L. T., Arrigo, K. R., & Grebmeier, J. M. (2021). Physical controls on the macrofaunal benthic biomass in Barrow Canyon, Chukchi Sea. *Journal of Geophysical Research: Oceans*, 126(5). <https://doi.org/10.1029/2020JC017091>

- Rand, K., Logerwell, E., Bluhm, B., Chenelot, H., Danielson, S. L., Iken, K., & Sousa, L. (2018). Using biological traits and environmental variables to characterize two Arctic epibenthic invertebrate communities in and adjacent to Barrow Canyon. *Deep Sea Research Part II: Topical Studies in Oceanography*, 152, 154–169. <https://doi.org/10.1016/j.dsr2.2017.07.015>
- Reynolds, O. (1883). An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Philosophical Transactions of the Royal Society of London*, 174, 935–982. <https://doi.org/10.1098/rstl.1883.0029>
- Sebens, K., Sarà, G., & Nishizaki, M. (2017). Energetics, particle capture, and growth dynamics of benthic suspension feeders. In *Marine Animal Forests* (pp. 1–42). Springer International Publishing. https://doi.org/10.1007/978-3-319-17001-5_17-3
- Snelgrove, P. V. R. (1998). The biodiversity of macrofaunal organisms in marine sediments. *Biodiversity and Conservation*, 7(9), 1123–1132. <https://doi.org/10.1023/A:1008867313340>
- Stabeno, P. J., Kachel, N., Ladd, C., & Woodgate, R. A. (2018). Flow patterns in the eastern Chukchi Sea: 2010–2015. *Journal of Geophysical Research: Oceans*, 123(2), 1177–1195. <https://doi.org/10.1002/2017JC013135>
- Timmermans, M., & Marshall, J. (2020). Understanding Arctic Ocean circulation: A review of ocean dynamics in a changing climate. *Journal of Geophysical Research: Oceans*, 125(4). <https://doi.org/10.1029/2018JC014378>
- Wood, K. R., Bond, N. A., Danielson, S. L., Overland, J. E., Salo, S. A., Stabeno, P. J., & Whitefield, J. (2015). A decade of environmental change in the Pacific Arctic region. *Progress in Oceanography*, 136, 12–31. <https://doi.org/10.1016/j.pocean.2015.05.005>
- Woodgate, R. A., Aagaard, K., & Weingartner, T. J. (2005). A year in the physical oceanography of the Chukchi Sea: Moored measurements from autumn 1990–1991. *Deep Sea Research Part II: Topical Studies in Oceanography*, 52(24–26), 3116–3149. <https://doi.org/10.1016/j.dsr2.2005.10.016>

Tables

| | Shannon-Weaver Diversity Indices | | |
|---------------|----------------------------------|-------------------|-------------------|
| | 2017 | 2019 | 2021 |
| BarC1 | 1.59* | 1.73* | 1.49* |
| BarC2 | 1.22 | 1.23 | 1.05 |
| BarC3 | 0.08 | 0.89 | 1.22 |
| BarC4 | 1.35 | 1.34 | 1.21 |
| BarC5 | 0.50 | 0.29 | 0.27 |
| BarC6 | 0.20 | 0.10 | 0.27 |
| BarC7 | 0.10 | 0.11 | 0.09 |
| BarC8 | 0.01 ⁺ | 0.07 ⁺ | 0.07 ⁺ |
| BarC9 | 0.26 | 0.45 | 0.26 |
| BarC10 | 0.33 | 0.55 | 0.53 |

Table 3.1 Shannon-Weaver Diversity Indices for 2017, 2019 and 2021 at each of the ten DBO5 Barrow Canyon (BarC) stations (BarC1-BarC10). Minimum values are indicated with ⁺ and maximum values are marked with *.

| Environmental Variable | p-value for the F-test | Conclusion |
|--|-----------------------------------|---|
| Shannon-Weaver Diversity Index | 0.75 | Fail to reject H ₀ No statistically significant differences |
| Bottom Water Temperature | 0.30 | Fail to reject H ₀ No statistically significant differences |
| Bottom Water Salinity | 0.41 | Fail to reject H ₀ No statistically significant differences |
| Bottom water chlorophyll-a | 0.23 | Fail to reject H ₀ No statistically significant differences |
| Surface sediment chlorophyll-a | 0.9 | Fail to reject H ₀ No statistically significant differences |
| Bottom water Silicate | 0.0014* | Reject H ₀ Statistically significantly variability |
| Bottom water Nitrate | 0.14 | Fail to reject H ₀ No statistically significant differences |
| Bottom water Phosphate | 0.097 | Fail to reject H ₀ No statistically significant differences |
| Bottom water Ammonia | 0.29 | Fail to reject H ₀ No statistically significant differences |
| Percentage of fine grain size in sediment ⁺ | 0.95 | Fail to reject H ₀ No statistically significant differences |
| Sediment Total Organic Carbon | 0.58 | Fail to reject H ₀ No statistically significant differences |
| Sediment Total Organic Nitrogen | 0.64 | Fail to reject H ₀ No statistically significant differences |

Table 3.2 Results of one-way ANOVA F-test for the differences in environmental variables across the study period along the DBO5 transect. The p-values are highlighted as follows:

- * significant: p-values between 0.05-.001
- *** highly significant: p-values ≤ 0.001

| Environmental Factors | Abundance and Diversity Variables | | | | |
|--|-----------------------------------|---------------------------------|------------------------------|--|---------------------------|
| | Overall Abundance | Abundance of Suspension Feeders | Abundance of Deposit Feeders | Abundance of Organisms that can suspension or deposit feed | Shannon Diversity Index |
| Depth | 0.71 0.0010*** | 0.22 0.2549 | 0.30 0.1322 | 0.70 0.0010*** | -0.31 0.0985 |
| Bottom Water Temperature | -0.32 0.1305 | 0.62 0.0005*** | 0.53 0.0070* | -0.51 0.0109* | 0.63 0.0004*** |
| Absolute Geostrophic Velocity of Non-upwelling Conditions | -0.14 0.4646 | 0.72 0.0004*** | 0.72 0.0007*** | -0.39 0.0358* | 0.62 0.0004*** |
| Range of Absolute Geostrophic Velocity from Non-upwelling conditions to upwelling conditions | -0.16 0.4413 | 0.75 0.0004*** | 0.69 0.0007*** | -0.42 0.0288* | 0.62 0.0004*** |
| Bottom water Salinity | 0.52 0.0726 | -0.45 0.01804* | -0.15 0.4397 | 0.63 0.0010*** | -0.62 0.0004*** |
| Bottom water chlorophyll-a | 0.38 0.0726 | -0.35 0.0656 | -0.16 0.4397 | 0.41 0.0288* | -0.40 0.0277* |
| Surface sediment chlorophyll-a | 0.41 0.0726 | -0.21 0.2921 | -0.15 0.4397 | 0.50 0.0150* | -0.34 0.0800 |
| Bottom water Silicate | 0.18 0.3911 | -0.69 0.0004*** | -0.55 0.0070* | 0.38 0.0382* | -0.54 0.0027* |
| Bottom water Nitrate | 0.25 0.2423 | -0.71 0.0005*** | -0.49 0.0131* | 0.47 0.0154* | -0.59 0.0010*** |
| Bottom water Phosphate | 0.34 0.1041 | -0.44 0.0196* | -0.33 0.0340* | 0.48 0.0150* | -0.47 0.0115* |
| Bottom water Ammonia | 0.51 0.0273* | -0.36 0.0654* | -0.38 0.0582 | 0.62 0.0010*** | -0.56 0.0019* |
| Percent of fine grain size in sediment [†] | 0.46 0.0353* | -0.65 0.0004*** | -0.37 0.0587 | 0.58 0.0010*** | -0.69 0.0004*** |
| Sediment Total Organic Carbon | 0.35 0.1041 | -0.52 0.0086* | -0.50 0.0146* | 0.47 0.0170* | -0.67 0.0004*** |
| Sediment Total Organic Nitrogen | 0.29 0.1922 | -0.52 0.0088* | -0.55 0.0070* | 0.41 0.0358* | -0.65 0.0004*** |

Table 3.3 Spearman's rank correlation coefficients in larger font on top and p-values with smaller font on bottom for the 70 tested correlations between overall station abundance, diversity, abundance of feeding groups (suspension, deposit and organisms that can engage in both) and 14 environmental variables. The p-values are adjusted with the Benjamini & Hochberg method and indicated with highlighting and notation as follows:

* significant: p-values between 0.05-.001
*** highly significant: p-values \leq 0.001

| Environmental Variable | Correlation to Abundance of <i>Elasipodida (O. glacialis)</i> (correlation coefficient and p-value) | One-way ANOVA (p-value) |
|--------------------------------|--|----------------------------|
| Bottom water Temperature | 0.32 <i>0.08</i> | 0.30 |
| Bottom water Salinity | -0.09 <i>0.65</i> | 0.41 |
| Bottom water chlorophyll-a | -0.28 <i>0.14</i> | 0.23 |
| Surface sediment chlorophyll-a | 0.01 <i>0.95</i> | 0.9 |
| Bottom water Silicate | -0.26 <i>0.17</i> | 0.0014* |
| Bottom water Nitrate | -0.46 <i>0.01*</i> | 0.14 |
| Bottom water Phosphate | -0.09 <i>0.64</i> | 0.097 |
| Bottom water Ammonia | -0.01 <i>0.94</i> | 0.29 |

Table 3.4 Spearman's rank correlation test results (coefficients in bold on top and p-values italicized below) between the abundance of the sea cucumber Order *Elasipodida (O. glacialis)* during 2017, 2019 and 2021 and eight environment variables including bottom water temperature, salinity, nutrients, and chlorophyll a (chl a). Surface sediment chlorophyll a (chl) a was also determined. Also included are the p-values for the One-way ANOVAs performed on the eight environmental variables to show if any of the variables correlated to *Elasipodida* abundance also vary significantly between 2017, 2019 and 2021.

* significant: p-values between 0.05-.001
 *** highly significant: p-values <0.001

Figures

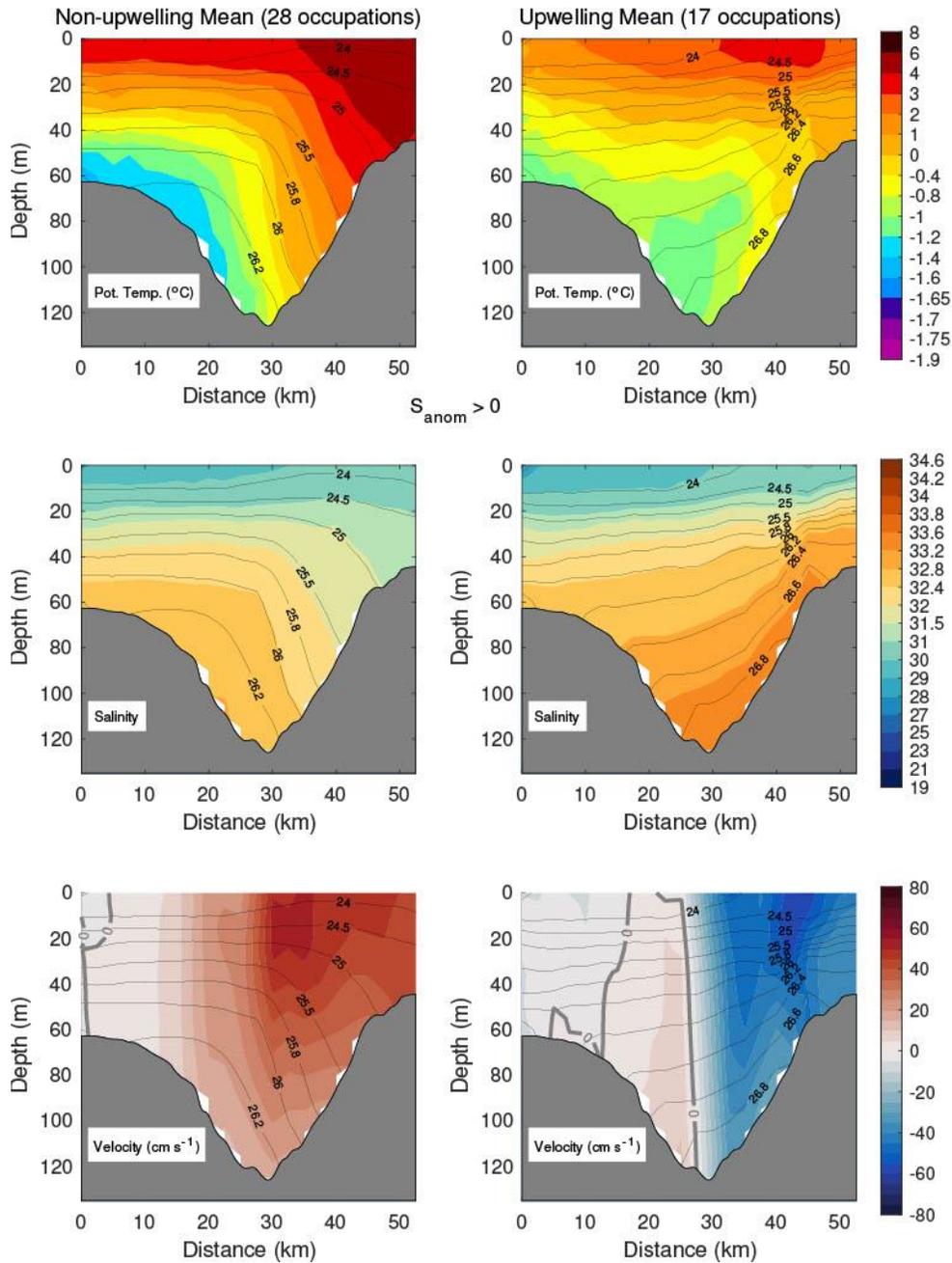


Figure 3.1 Temperature, salinity and velocity gradients observed across the DBO5 line with BarC1 located on the right side of each figure, BarC5 at 30 km distance and BarC10 located on the left side of the figure. These figures show mean values derived from 28 Non-Upwelling occupations and 17 Upwelling occupations and were made using MATLAB programming language and numeric computing environment developed by MathWorks (<https://www.mathworks.com/>). Figures and data courtesy of Dr. Robert Pickart of Woods Hole Oceanographic Institution.

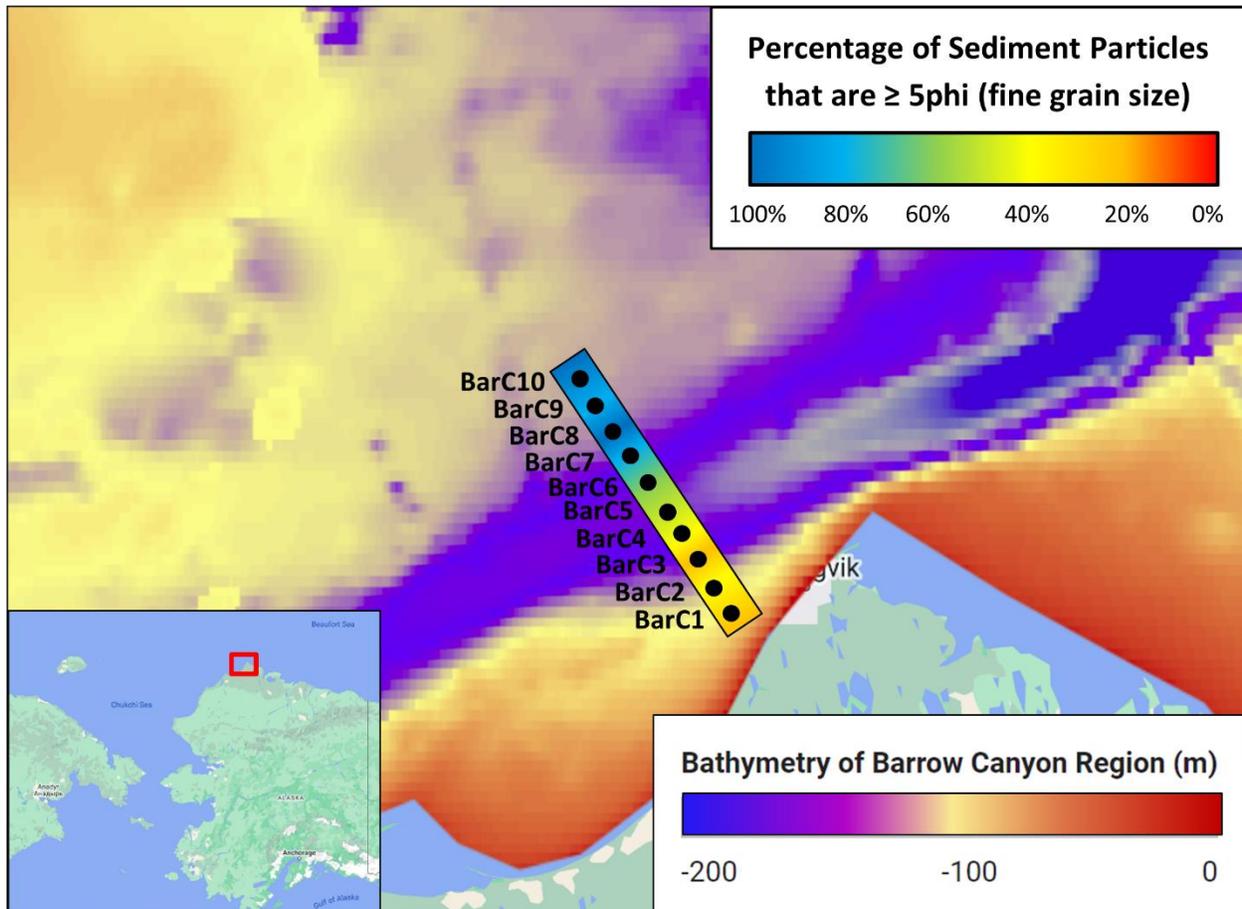
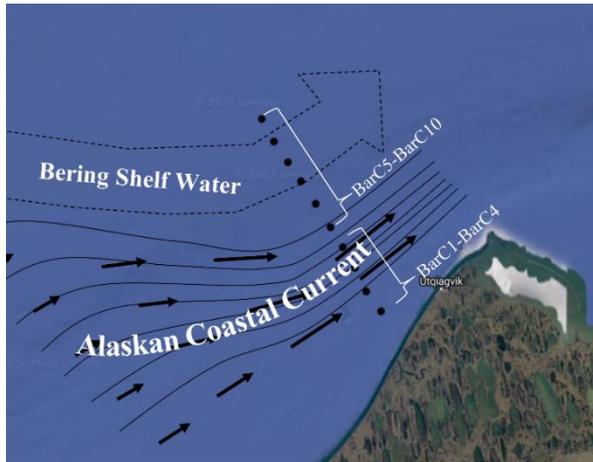
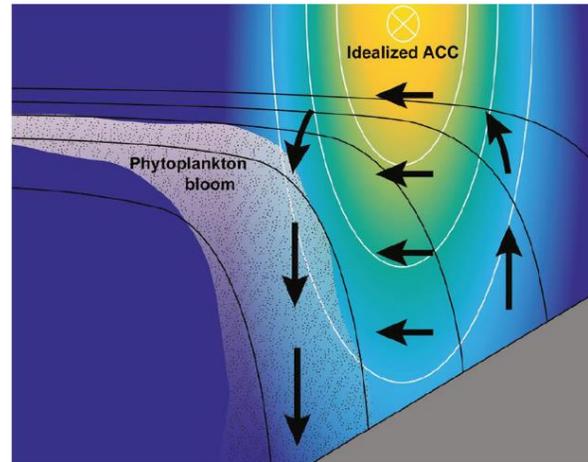


Figure 3.2 A map of the ten stations that make up the DBO5 sampling transect. Also displayed is the bathymetry of the Barrow Canyon region and percentage of sediment particles that are equal to or over a given threshold of fineness (5 phi on the Krumbein phi scale) These variables are shown via two different color bar scales which are denoted on the map. The base map was prepared using Google Earth Engine, the bathymetry data is sourced from the Google Earth Engine data set (Amante & Eakins, 2009) and the grain-size data is an average value collected on the CCGS Sir Wilfrid Laurier occupations of the DBO5 line during 2017, 2019 and 2021. The ten stations (BarC1-BarC10) are denoted by the black dots and labeled. This figure shows that the inshore slope of Barrow Canyon (BarC1-BarC5) is predominately characterized by lower percentages of finer sediments (i.e. coarser sediments) while the offshore slope of Barrow Canyon (BarC6-BarC10) contains higher percentages of finer sediments.

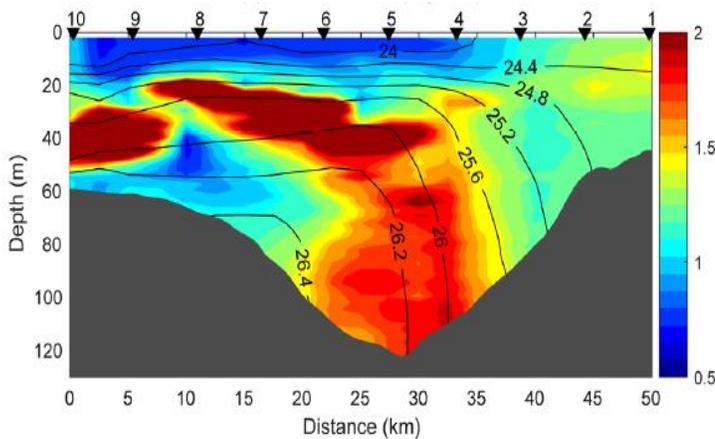
a) Flow in the horizontal plane



b) flow in the vertical plane



c) Fluorescence (mg m^{-3})



d) Chlorophyll-a Concentrations and DBO5 source region

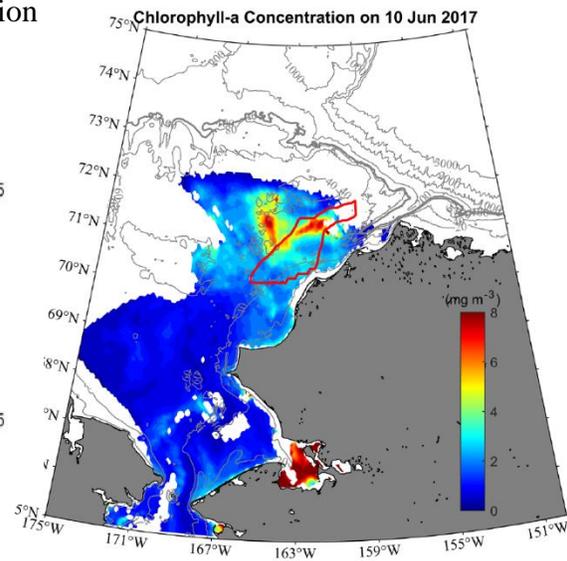


Figure 3.3 a) The DBO5 transect with an overlaid schematic of the flow of the two primary water masses present in Barrow Canyon: the inshore Alaskan Coastal Water and offshore Bering Sea Water. b) a vertical transect of the inshore slope of Barrow Canyon with an idealized version of the vertical advection cell caused by current interactions that advect food sources directly to the trough of the Canyon. c) a vertical transect of fluorescence (mg m^{-3}) along the DBO5 transect with station position denoted along the top of the figure. This figure shows data which supports the idealized vertical advection cell shown in figure 3.3b. d) Chl a concentration based on the MODIS image for June 10, 2017. The red outlined region corresponds with the DBO5 source region which can be seen in Figure 1.4. Image a) is adapted from Pickart et al. (2021) while images b), c), and d) are sourced from Pickart et al. (2021)

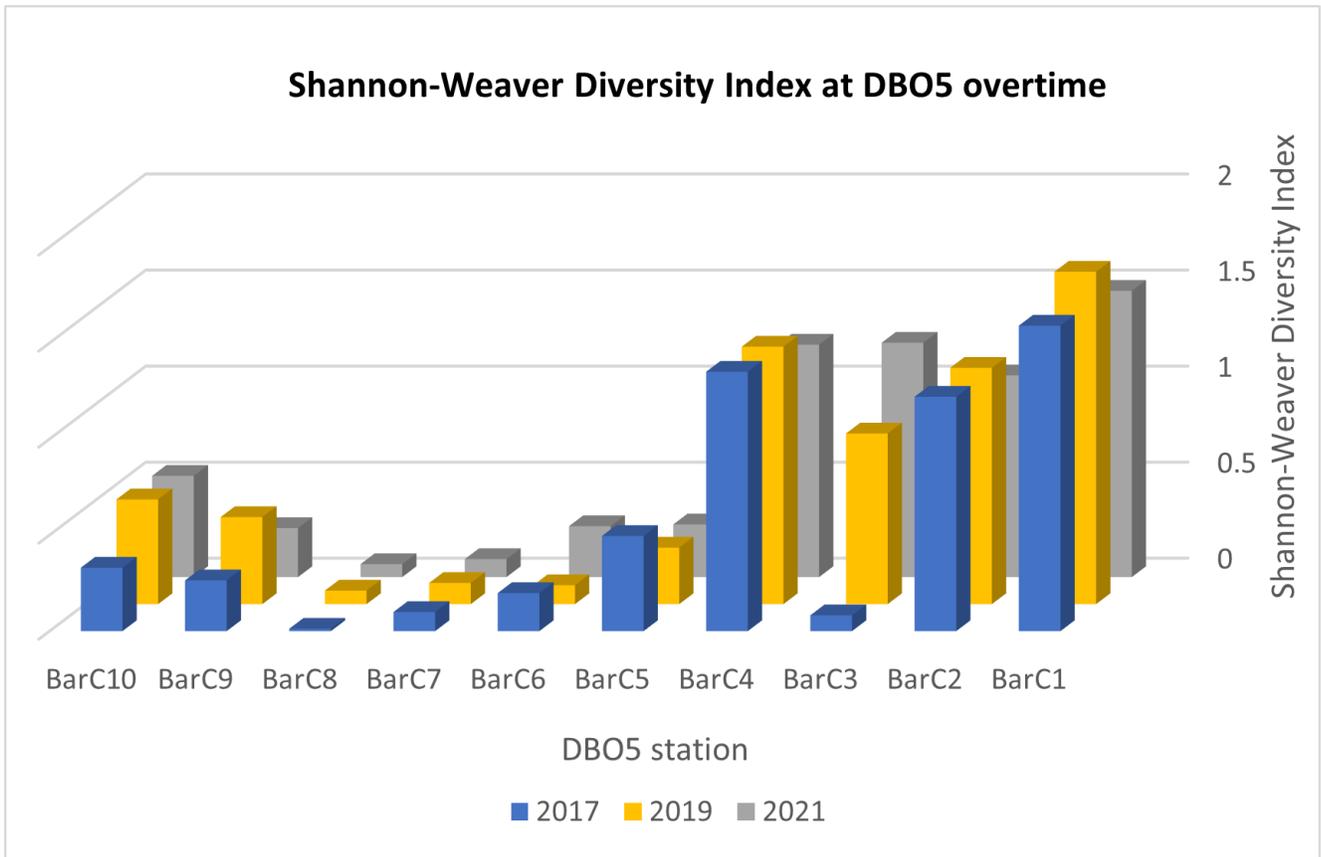


Figure 3.4 Shannon-Weaver Diversity Indices values at DBO5 during 2017, 2019 and 2021. Minimum Indices are observed all three years at BarC8 while maximum Indices are observed all three years at BarC1. Specific values are referenced in Table 3.1. The plot was prepared using Microsoft Excel.

Average Total Abundance vs Average Diversity at DBO5

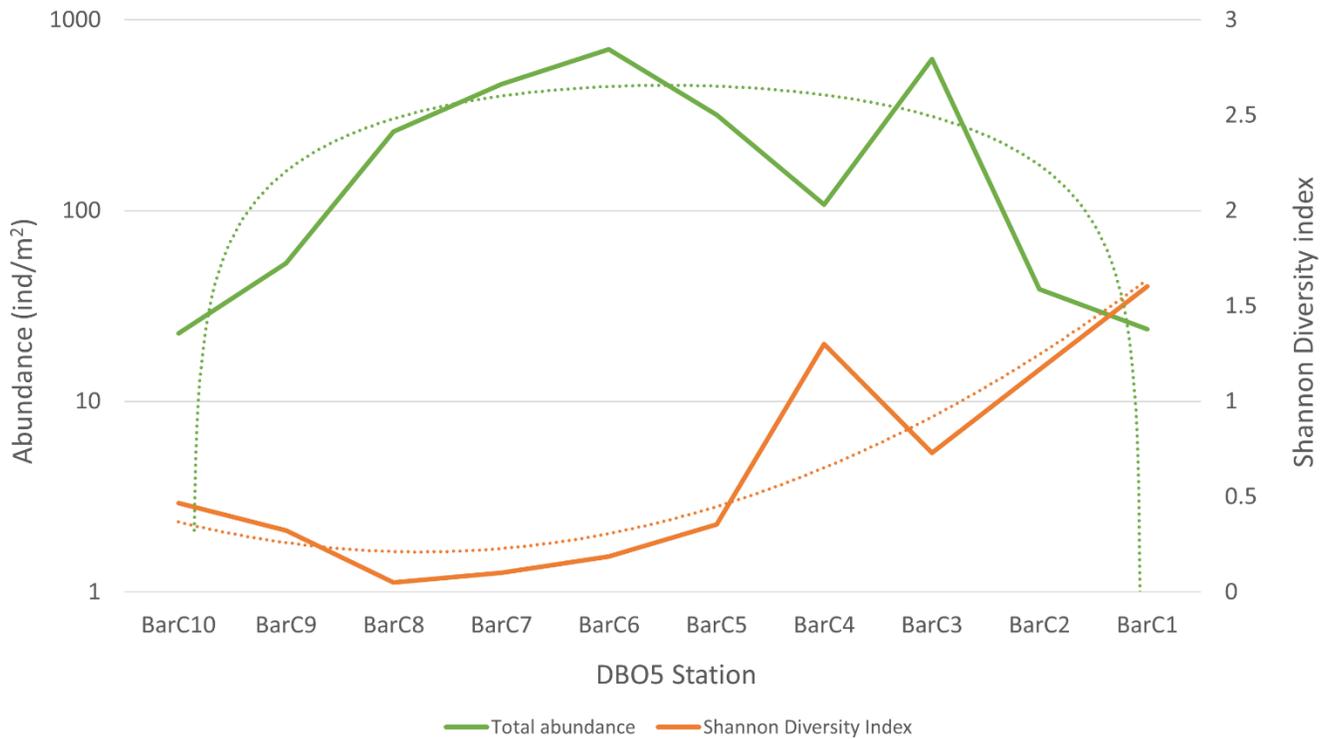


Figure 3.5 Mean total abundance and diversity from the study years at each station along the DBO5 transect. Abundance is measured in individuals per meter² (ind/m²) and graphed in green with values logarithmically displayed on the left y-axis. The Shannon Diversity Indices are graphed in orange with values shown on the right y-axis. Abundance peaks near the trough of the Canyon at BarC6 and generally decrease bidirectionally while diversity reaches a minimum at BarC8 and increases bidirectionally. Plot prepared using Microsoft Excel.

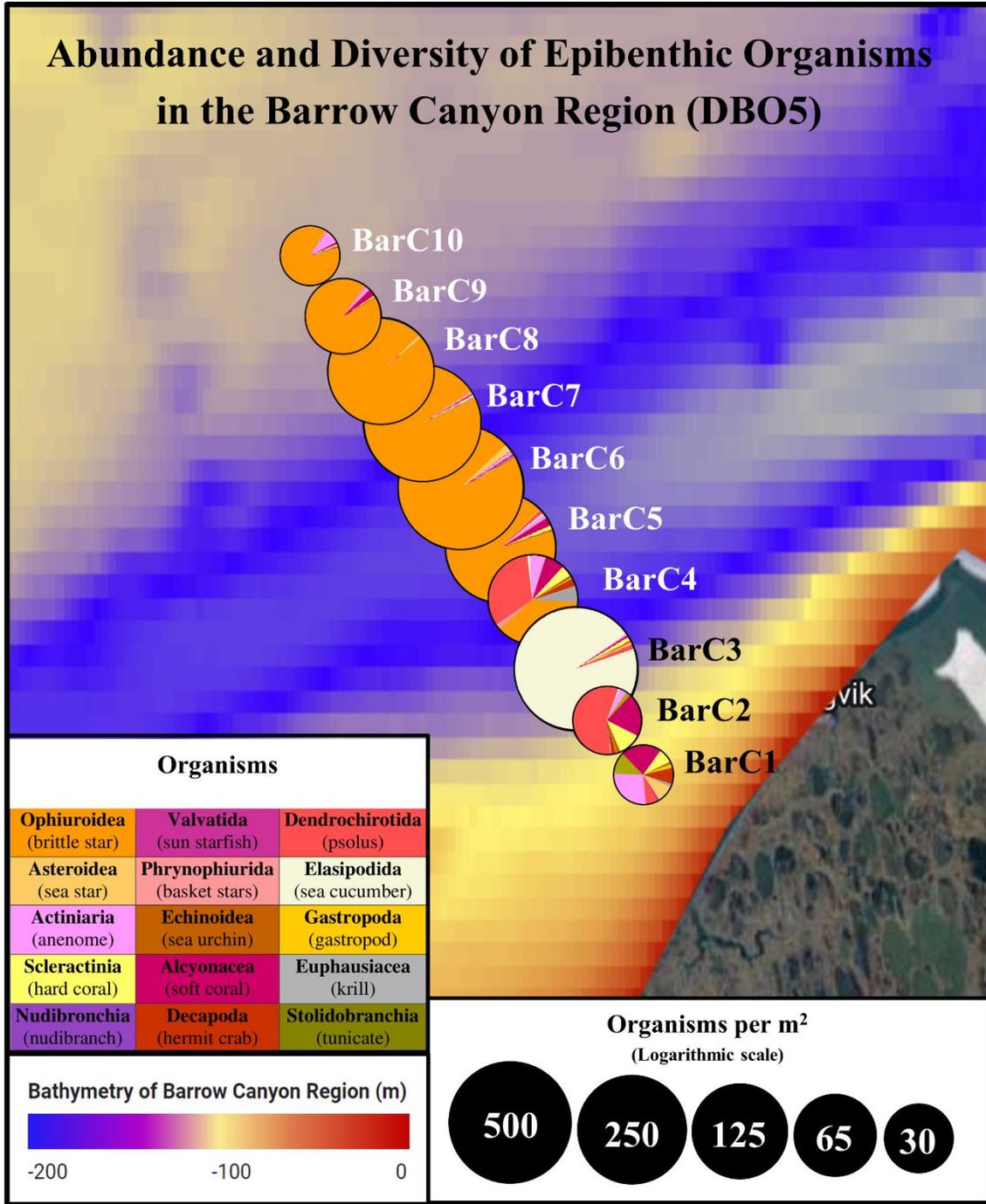


Figure 3.6 Abundance and diversity at the 10 stations that make up the DBO5 transect (BarC1- BarC10) overlaid on bathymetry of the region. Abundance is shown as the size of the pie symbol scaled logarithmically for ease of visualization and the 15 groupings of organism counted are each displayed by a different color in the pie chart. The base map was prepared using Google Earth Engine and bathymetry data sourced from the Google Earth Engine data set (Amante & Eakins, 2009).

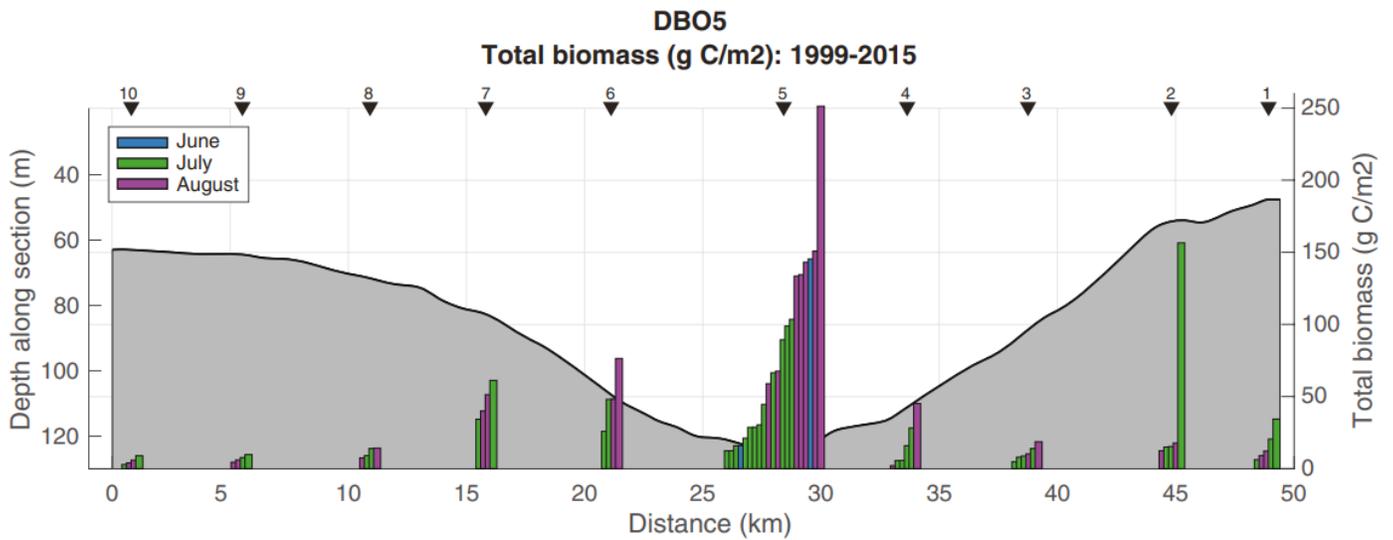


Figure 3.7 Distribution of monthly infauna biomass across the DBO5 line using data from 1999 to 2015 overlaid upon a bathymetry curve (grey). The ten sampling stations are marked along the upper x axis. The bathymetry is from the USGCS Healy echosounder. See Grebmeier and Cooper (2020) for methods and cruise information. Sourced from Pickart et al. (2021).

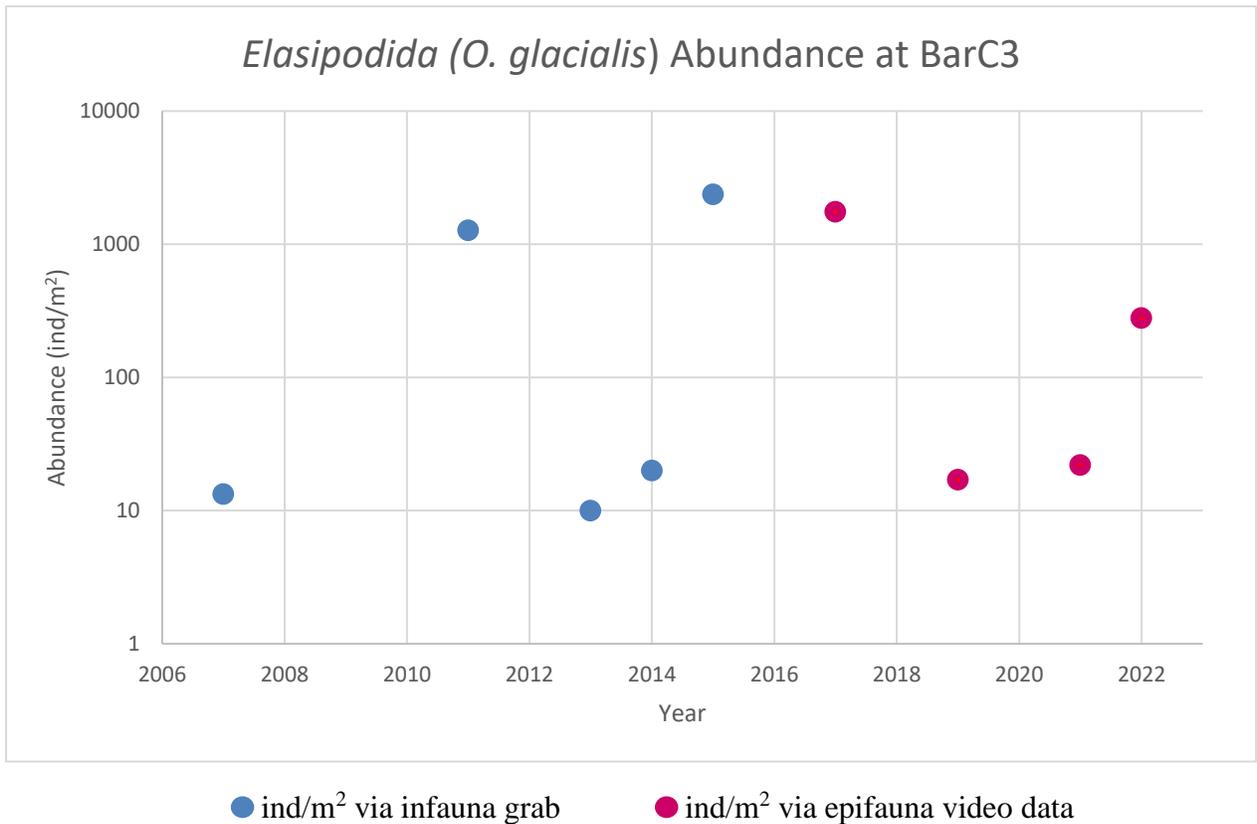


Figure 3.8 Abundance of *Elasipodida (O. glacialis)* from 2007 to 2022 utilizing available years of data from benthic infauna Van Veen grabs and epibenthic Drop Camera Video System (DCVS) data. Note: abundance is graphed logarithmically.

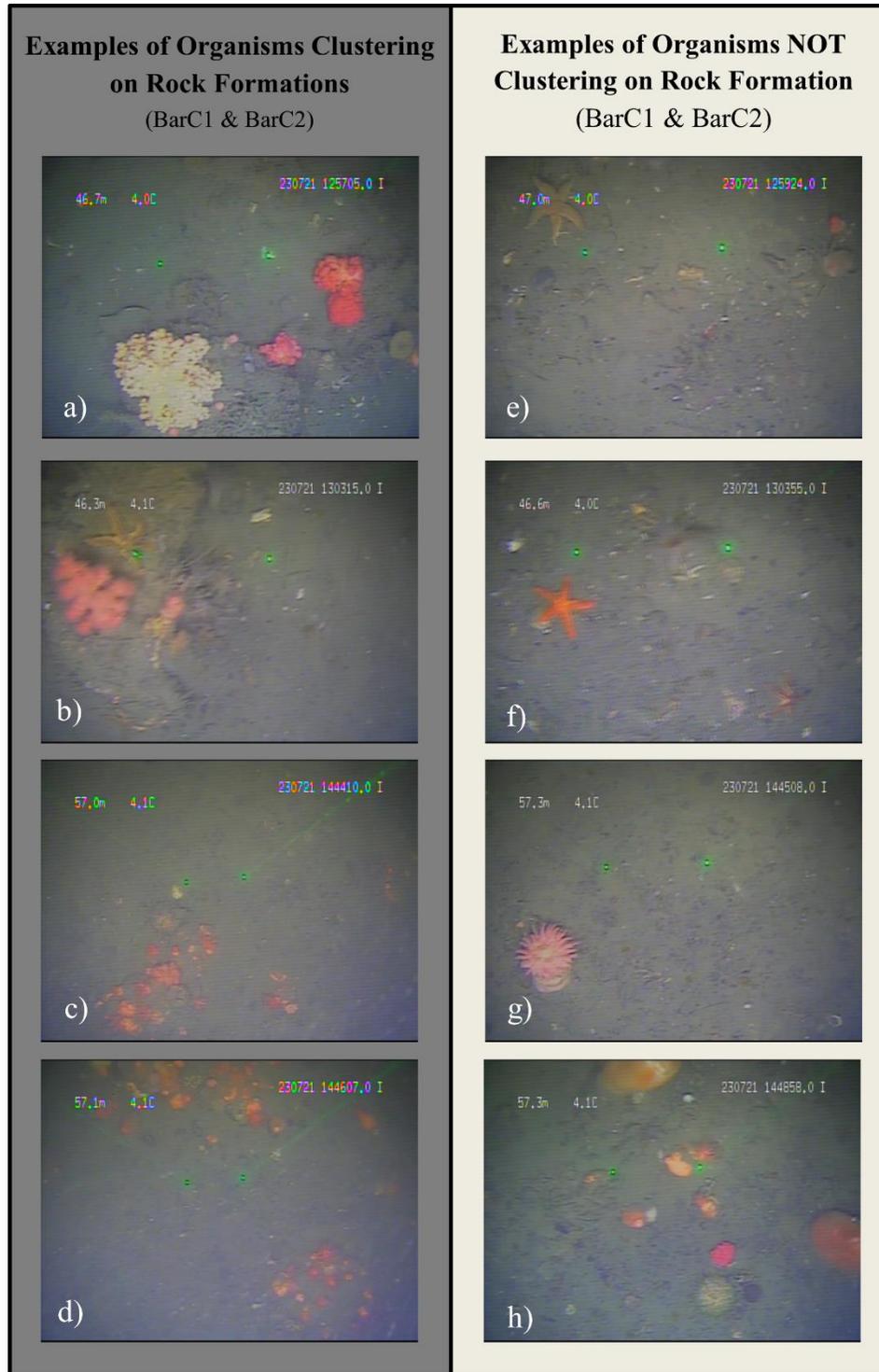


Figure 3.9 Example images of organisms clustering on rock formations as well as example of more random distribution of organisms across the benthos at the same stations. Images a), b), e), and f) are taken from 2021 data at BarC1 while images c), d), g), and h) are taken from 2021 data at BarC2.

Appendix 2

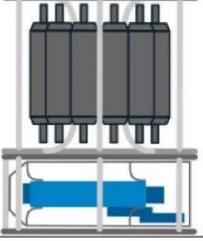
Several DBO associated data sets are used as a part of this study. Instruments used to collect these data include the DCVS, ADCP, CTD and associated Niskin bottles on rosette and a van Veen grab (Figure A2.1).

The DCVS collects video files which are used for epifaunal abundance and diversity data. DCVS data were collected aboard the CCGS Sir Wilfrid Laurier in July of 2017, 2019 and 2021. Additional information on uses, set up and deployment can be found in Chapter 2 and Appendix 1.

ADCP data are all collected aboard the USCGC Healy, during 45 occupations of the DBO5 line between the months of July thru October in the years 2009-2021. The ADCP is built into the ship and raw data are collected continuously. Data are processed in conjunction with CTD measurements to calculate the absolute geostrophic velocity of currents during station occupation (Pickart et al., 2021). The values used in this study are means from 28 Non-upwelling occupation and 17 Upwelling occupations.

The CTD and Niskin bottle rosette are attached to the same frame and used to profile salinity and temperature as well as collect water samples at discrete depths. This produces the following data used in this study: bottom water temperature, salinity, chl a, and nutrients, which are also available from Grebmeier & Cooper (2020).

The 0.1 m² Van Veen grab used for the collection of sediment samples and macroinfauna is weighted with 32kg lead to enhance penetration into the sediments. The CTD, rosette and grab data used in this study were collected aboard the CCGS Sir Wilfrid Laurier in July of 2017, 2019 and 2021 (Grebmeier & Cooper, 2020).

| Instrument Name | Graphic | Details | Data Sets (used for this study) |
|---|---|--|--|
| Drop Camera Video System (DCVS) |  | <ul style="list-style-type: none"> collects raw video clips of benthic environment additional information on setup and deployment can be found in Appendix 2 | <ul style="list-style-type: none"> Abundance Diversity Feeding Group Abundance <p><i>Data years: 2017, 2019 and 2021</i></p> |
| Acoustic Doppler Current Profiler (ADCP) |  | <ul style="list-style-type: none"> uses sound waves to measure the speed and direction of currents throughout the water column | <ul style="list-style-type: none"> Absolute Geostrophic Velocity of Non-upwelling conditions Range of Absolute Geostrophic Velocity between Non-upwelling and Upwelling conditions <p><i>data courtesy of Dr. Robert Pickart of Woods Hole Oceanographic Institution</i></p> <p><i>Data years: 2009-2021</i></p> |
| Conductivity Temperature and Depth (CTD) |  | <ul style="list-style-type: none"> refers to a package of electronic devices which profiles conductivity and temperature relative to depth used onboard the same frame as the Rosset of Niskin bottles | <ul style="list-style-type: none"> Bottom Water Temperature Bottom Water Salinity <p><i>Data years: 2017, 2019 and 2021</i></p> |
| Rosette of Niskin Bottles |  | <ul style="list-style-type: none"> electronically trigger collection bottles used to collect discrete water samples at specific depths used onboard the same frame as the CTD | <ul style="list-style-type: none"> Bottom Water chlorophyll a Bottom Water nutrients: Silicate, Nitrate, Phosphate and Ammonia <p><i>Data years: 2017, 2019 and 2021</i></p> |
| Van Veen Grab |  | <ul style="list-style-type: none"> a sediment and infauna sampler that has a clam shell-type scoop setup grab is manually trigger by contacting the benthos | <ul style="list-style-type: none"> Sediment chlorophyll a Sediment Grain size Sediment Total Organic Carbon Sediment Total Organic Nitrogen <p><i>Data years: 2017, 2019 and 2021</i></p> <ul style="list-style-type: none"> abundance of Elaspodida (<i>O. glacialis</i>) (Figure 3.8) <p><i>Data years: 2007, 2011, 2013-2015</i></p> |

a. https://www.comm-tec.com/Images/Products/RDI/web_monitor1105.jpg

b. Created by Brn-Brn and licensed under the Creative Commons Attribution-Share Alike 3.0 Unported

c. Created by Hans Hillewaert and licensed under the Creative Commons Attribution-Share Alike 3.0 Unported

Figure A2.1 Information on sampling instruments, related data and collection years used as a part of this study.

Chapter 4: Conclusions

The Role of Drop Camera Video Data in Assessing Abundance and Diversity of Epibenthic Organisms in Today's Arctic Research

The use of video data in the Pacific Arctic Region (PAR) is a powerful tool and the continued expansion of its use and analysis will further facilitate our understanding of the epibenthic assemblages on local and regional scales and how the assemblages may shift with changing environment conditions. Chapter 2 and 3 establishes the importance and potential of the Drop Camera Video System (DCVS) through video data collected as a part of the Distributed Biological Observatory (DBO) (<http://www.arctic.noaa.gov/dbo/about>) aboard the Canadian Coast Guard Ship Sir Wilfrid Laurier (CCGS SWL) in the Northeastern Chukchi Sea's Barrow Canyon (Figure 1.3). The DBO is an ongoing international ocean observing network committed to establishing a change detection array in the PAR. This is accomplished with repeated long-term water column and benthic sampling along multiple transects across benthic biological hotspots in the northern Bering and Chukchi Seas. Transect DBO5 runs perpendicular to the axis of Barrow Canyon, approximately 60 nautical miles from its head (Figure 1.1, 1.2). The Canyon's rocky sediments make it challenging to sample with traditional epifauna and infauna sample collection equipment (i.e. trawls and grabs). Traditional sampling challenges in tandem with variable benthic abundance and diversity across the Canyon make this an ideal spot for DCVS sampling.

The studies presented in this thesis expand upon existing epibenthic studies in the Barrow Canyon region by providing a finer scale assessment of epifaunal abundance and taxonomic diversity across the inshore and offshore slopes of the Canyon rather than a comparison of Barrow Canyon's epibenthos to the surrounding shelf region (Iken et al., 2019; Rand et al., 2018). This is possible because of the unique properties of DCVS sampling which allow for standardized

sampling across a variety of bottom conditions and characteristics. Chapter 2 establishes that overall epifaunal abundance data are normally distributed across the Canyon with peak faunal abundance near the deepest sampling location likely due to vertical transport of food as determined by a previous modeling study (Pickart et al. 2021). Chapter 3 shows that epifaunal diversity is higher along the in-shore slope coincident with the faster currents, warmer temperatures, and fresher conditions of the Alaskan Coastal Water (ACW). This enhances our understanding of Barrow Canyon as not only a benthic biological hotspot but an ecosystem that supports several epibenthic niches within a limited area. The statistical analysis of correlations between environmental conditions and biological variables presented in Chapter 3 suggests that changes in the prevailing currents in the Canyon may impact the future abundance and diversity of epibenthic species in the Canyon. While the magnitude and longevity of impact is beyond the scope of the currently available data, other studies predict changes in regional environmental conditions are likely (Armitage et al., 2020; Box et al., 2019; Frey et al., 2021; Gaffey et al., 2022; Grebmeier et al., 2015, 2019; Mueter et al., 2021; Pickart et al., 2021; Stabeno et al., 2016, 2018; Wood et al., 2015).

In addition to shifting environmental conditions that could impact the Canyon's epibenthic populations, changes in benthic diversity, which is a proxy for ecosystem health, could impact the Canyon's ability to support the higher trophic species that rely on the regional productivity. Currently the variety of upper trophic seabirds and marine mammals can all be found off the coast of Utqiagvik, AK including king eiders (*Somateria spectabilis*), beluga (*Delphinapterus leucas*) and gray whales (*Eschrichtius robustus*) as well as Pacific walrus (*Odobenus rosmarus divergens*), polar bears (*Ursus maritimus*), spotted seals (*Phoca largha*), bearded seals (*Erignathus barbatus*), and ringed seal (*Pusa hispida*) (Clarke et al., 1993; Jay et al., 2012; Moore et al., 2014; Oppel et

al., 2009; Smith et al., 2014). These species, among others are partially supported through a diverse benthic food web (Grebmeier et al., 2010; Moore et al., 2014). If the inshore benthic diversity correlated to the Alaskan Coastal Current (ACC) is affected by predicted possible changes in the ACC, or even on a larger scale to the location of Bering Shelf and Anadyr Water, the Chukchi Slope Current and the Beaufort Gyre, there could be cascading impacts to higher trophic levels via the food web (Armitage et al., 2020; Box et al., 2019; Grebmeier et al., 2010; Moore et al., 2014; Pickart et al., 2021). Therefore, the results presented in this study support the expansion of DCVS data sets to produce more robust time-series analysis. Ultimately these time-series and modeling of both epifaunal abundance and diversity coincident with environmental data collections will lead to better understanding of changes in the biological system that could impact overall ecosystem health.

Review of Project Goals and Key Findings

Chapter 2 of this thesis establishes standard collection, processing, and analysis techniques for DCVS video data as well as presenting epifaunal abundance and feeding group distribution data across Barrow Canyon during 2017, 2019 and 2021. Using one-way Analysis of Variance (ANOVA) tests and Shapiro-Wilk test for normality, the overall epifaunal abundance as well as the abundance of key epifaunal species and different feeding groups were analyzed to assess if epifaunal abundance was normally distributed across the Canyon and whether there were statistically significant changes during the study years. The most notable finding from this analysis was that the overall mean abundance of epibenthic species as well as the mean abundance of three major epifaunal feeding categories (deposit, suspension, and both) did not significantly vary across the Canyon throughout the study years (Table 2.3). This suggests that within the limited timespan of data available, there are not significant and persistent changes to the epibenthic population on a

broad scale across the Canyon. Looking at individual organism populations, there are also not significant variations in the mean abundance of the three most prevalent organisms across the Canyon (Ophiuroidea, Elaspodida, Dendrochirotida); however, there are significant variations during the study period in less prevalent organisms (Alcyonacea, Gastropoda, Decapoda) (Table 2.3). This may suggest a minor restructuring of the epibenthic assemblage among the less prevalent species; however, most of the organisms exhibiting significant variations are epifauna with higher mobility (Decapoda and Gastropoda) meaning their variation could be a result of their movement and lower abundance which increases the variability in the observed locations. In the end I conclude that there is not sufficient evidence for major changes or trends within the epibenthic population overall or at a lower taxonomic level during the timeframe of the study in Barrow Canyon.

In addition to analysis of variance, in Chapter 2 Shapiro-Wilk normality tests show that overall epifaunal abundance is normally distributed across the Canyon but the abundance of Ophiuroidea (brittle stars), which are the most prevalent epibenthic organisms in the region, are non-normally distributed (Table 2.3). This suggests that there are changes in environmental conditions across the Canyon which cause a spatial zonation of epibenthic fauna and non-uniform distribution of species. This aligns with the Spearman's rank correlation coefficient tests performed in Chapter 3. Of the 70 correlation tests performed, the most notable results indicate that overall epifaunal abundance was most significantly correlated to depth, while Shannon-Weaver Diversity Indices (SWDI) and obligate suspension or deposit feeders were correlated to water mass variables, such as current speeds and bottom water temperature, salinity, and nutrients (Table 3.3). The correlation assessments shows that diversity and the abundance of obligate epifaunal suspension or deposit feeders are greater in faster currents, higher temperatures, fresher

water, and in the presence of lower concentrations of nutrients. These conditions predominate along the inshore slope of Barrow Canyon, which is impacted by the Alaska Coastal Water (ACW) in comparison with the offshore slope that is more influenced by Bering Sea Water (BSW). The presence of organisms that can be either suspension or deposit feeder are negatively correlated to the physical and chemical conditions that promote higher diversity. Essentially this means that the abundance of this flexible feeding type is significantly correlated to slower currents, a smaller range of absolute geostrophic velocity, lower bottom water (BW) temperatures, higher BW salinity, and higher BW nutrients. A specific example of this is the abundances of Ophiuroidea (brittle stars), which are by far the most predominant organisms of this feeding type. Ophiuroidea can be found chiefly along the offshore slope of Barrow Canyon where the slower, colder, saltier, and more nutrient rich BSW is located. This aligns with the results from Chapter 2 that suggest overall epifaunal organism abundance is normally distributed across the Canyon's relatively symmetrical depth profile with the highest abundance (density of organisms) at the deepest sampling stations, while the populations of different organisms are skewed toward the offshore or inshore slope of the Canyon. Chapter 3 builds upon this understanding by showing that environmental variables impacted by prevailing water masses (the inshore ACW vs the offshore BSW) affect not only the epifaunal organisms found in each location, but the taxonomic and functional diversity of these organisms on both of the Canyon's slopes.

The results in both Chapter 2 and Chapter 3 indicate that there is strong spatial zonation of epibenthic organisms and diversity across the Canyon's inshore and offshore slope even though overall abundance peaks in the Canyon's trough. This zonation is associated with the physical and chemical regimes that bring together the converging water masses that are then transported offshore via the Canyon. Therefore, while there have been no major changes observed in either

epifaunal abundance or diversity across the Canyon, the epibenthic assemblage and associated biological hotspot that is currently present are a function of the balance of currents that transport two distinct water masses through the Canyon. This makes the abundance, diversity and, potentially, overall health of the Canyons' epibenthic population vulnerable to future changes if the prevailing currents change in response to increased sea ice melt, warming temperatures and higher inputs of freshwater to the Arctic system (Armitage et al., 2020; Stabeno et al., 2016, 2018; Timmermans & Marshall, 2020). Thus, continued observation via DCVS data is needed to catalog and understand what, if any, changes may occur in the future.

Future Work

The results presented in this thesis establish the versatility and applicability of the DCVS and encourage both the temporal and spatial expansion of this work. As previously discussed, while there were no major changes observed in the epibenthic population between the study years (2017, 2019 and 2021), there is a possibility for the destabilization of the benthic biological system and its biodiversity due to changes in the region's converging currents. Similar changes are already underway in infaunal and epifaunal populations across the PAR (Danielson et al., 2022; Goethel et al., 2019; Grebmeier, 2012; Grebmeier et al., 2006, 2010, 2018, 2019; Mueter et al., 2021; Rand et al., 2018) and could become significant in Barrow Canyon. Thus, to catalog and understand these changes when and if they occur, continued sampling and analysis of DCVS DBO5 epifaunal data is needed to create lengthier time series that can be used to detect trends and model future abundance and diversity. In addition to adding additional years of data, expanding the spatial area where DCVS data can be collected will further our understanding not only of local but regional trends of epibenthic abundance and diversity. The DCVS has been historically used across the DBO1-DBO5 regions which gives ample data for future analysis highlighting one of the strengths

of DCVS data, which is the ability to refer to the original sample which is unaltered by time or preservation methods (Bethoney & Stokesbury, 2018). While the sampled transects at DBO1-4 do not exhibit similar physical benthic constraints as DBO5, which alone has in parts a rocky bottom that make traditional epibenthic sampling impractical, the rapid and cost-effective nature of the DCVS still make it a useful option for regional understanding of epibenthic populations. The methods and results presented in this thesis not only inform our understanding of Barrow Canyon as a local system, but show the possibilities for future expansion of DCVS abundance and diversity studies to other DBOs.

In addition to abundance and diversity, the methods established in this thesis could also lend themselves for size class analysis of epibenthic species. While traditional epibenthic sampling often results in biomass studies that are not possible with strictly visual data, size class studies would be possible using software such as ImageJ that was used for image processing in this thesis. Using the known actual and pixel distance between the DCVS positioning lasers, the size of target organisms could be measured within sampled frames and a size class data set for a spatial or time-series analysis would be practical. This would extend DCVS video data to further inform the health of the epibenthic system in the Arctic and how the size of a species varies or may be changing. This would be a powerful next step for Pacific Arctic video data and increase its ability to contribute useful and informative data sets to the larger DBO data sharing network.

References

- Armitage, T. W. K., Manucharyan, G. E., Petty, A. A., Kwok, R., & Thompson, A. F. (2020). Enhanced eddy activity in the Beaufort Gyre in response to sea ice loss. *Nature Communications*, *11*(1). <https://doi.org/10.1038/s41467-020-14449-z>
- Bethoney, N. D., & Stokesbury, K. D. E. (2018). Methods for image-based surveys of benthic macroinvertebrates and their habitat exemplified by the drop camera survey for the Atlantic sea scallop. *Journal of Visualized Experiments*, *137*. <https://doi.org/10.3791/57493>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F. J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., & Olsen, M. S. (2019). Key indicators of Arctic climate change: 1971-2017. *Environmental Research Letters*, *14*(4). <https://doi.org/10.1088/1748-9326/aafc1b>
- Clarke, J., Moore, S., & Johnson, M. (1993). Observations on beluga fall migration in the Alaskan Beaufort Sea, 1982-87, and Northeastern Chukchi Sea, 1982-91. *Report to the International Whaling Commission*, *43*, 387.
- Danielson, S. L., Grebmeier, J. M., Iken, K., Berchok, C., Britt, L., Dunton, K., Eisner, L., Farley, E., Fujiwara, A., Hauser, D., Itoh, M., Kikuchi, T., Kotwicki, S., Kuletz, K., Mordy, C., Nishino, S., Peralta-Ferriz, C., Pickart, R., Stabeno, P. J., ... Woodgate, R. A. (2022). Monitoring Alaskan Arctic Shelf ecosystems through collaborative observation networks. *Oceanography*. <https://doi.org/10.5670/oceanog.2022.119>
- Frey, K. E., Comiso, J. C., Cooper, L. W., Grebmeier, J. M., & Stock, L. V. (2021). Arctic Ocean primary productivity: The response of marine algae to climate warming and sea ice decline. *Arctic Report Card*. <https://doi.org/10.25923/kxhb-dw16>
- Gaffey, C. B., Frey, K. E., Cooper, L. W., & Grebmeier, J. M. (2022). Phytoplankton bloom stages estimated from chlorophyll pigment proportions suggest delayed summer production in low sea ice years in the northern Bering Sea. *PLOS ONE*, *17*(7), e0267586. <https://doi.org/10.1371/journal.pone.0267586>
- Goethel, C. L., Grebmeier, J. M., & Cooper, L. W. (2019). Changes in abundance and biomass of the bivalve *Macoma calcarea* in the northern Bering Sea and the southeastern Chukchi Sea from 1998 to 2014, tracked through dynamic factor analysis models. *Deep Sea Research Part II: Topical Studies in Oceanography*, *162*, 127–136. <https://doi.org/10.1016/j.dsr2.2018.10.007>

- Grebmeier, J. M. (2012). Shifting patterns of life in the Pacific Arctic and sub-Arctic Seas. *Annual Review of Marine Science*, 4, 63–78. <https://doi.org/10.1146/annurev-marine-120710-100926>
- Grebmeier, J. M., Bluhm, B. A., Cooper, L. W., Danielson, S. L., Arrigo, K. R., Blanchard, A. L., Clarke, J. T., Day, R. H., Frey, K. E., Gradinger, R. R., Kędra, M., Konar, B., Kuletz, K. J., Lee, S. H., Lovvorn, J. R., Norcross, B. L., & Okkonen, S. R. (2015). Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. *Progress in Oceanography*, 136, 92–114. <https://doi.org/10.1016/j.pocean.2015.05.006>
- Grebmeier, J. M., Frey, K., Cooper, L., & Kędra, M. (2018). Trends in benthic macrofaunal populations, seasonal sea ice persistence, and bottom water temperatures in the Bering Strait region. *Oceanography*, 31(2). <https://doi.org/10.5670/oceanog.2018.224>
- Grebmeier, J. M., Moore, S. E., Cooper, L. W., & Frey, K. E. (2019). The Distributed Biological Observatory: A change detection array in the Pacific Arctic – An introduction. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 1–7. <https://doi.org/10.1016/j.dsr2.2019.05.005>
- Grebmeier, J. M., Moore, S. E., Overland, J. E., Frey, K. E., & Gradinger, R. (2010). Biological response to recent Pacific Arctic sea ice retreats. *Eos, Transactions American Geophysical Union*, 91(18), 161. <https://doi.org/10.1029/2010EO180001>
- Grebmeier, J. M., Overland, J. E., Moore, S. E., Farley, E. V., Carmack, E. C., Cooper, L. W., Frey, K. E., Helle, J. H., McLaughlin, F. A., & McNutt, S. L. (2006). A major ecosystem shift in the Northern Bering Sea. *Science*, 311(5766), 1461–1464. <https://doi.org/10.1126/science.1121365>
- Iken, K., Mueter, F., Grebmeier, J. M., Cooper, L. W., Danielson, S. L., & Bluhm, B. A. (2019). Developing an observational design for epibenthos and fish assemblages in the Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 180–190. <https://doi.org/10.1016/j.dsr2.2018.11.005>
- Jay, C. V., Fischbach, A. S., & Kochnev, A. A. (2012). Walrus areas of use in the Chukchi Sea during sparse sea ice cover. *Marine Ecology Progress Series*, 468, 1–13. <https://doi.org/10.3354/meps10057>
- Moore, S. E., Logerwell, E., Eisner, L., Farley, E. V., Harwood, L. A., Kuletz, K., Lovvorn, J., Murphy, J. R., & Quakenbush, L. T. (2014). Marine fishes, birds and mammals as sentinels of ecosystem variability and reorganization in the Pacific Arctic region. In *The Pacific Arctic Region* (pp. 337–392). Springer Netherlands. https://doi.org/10.1007/978-94-017-8863-2_11

- Mueter, F., Iken, K., Cooper, L., Grebmeier, J. M., Kuletz, K., Hopcroft, R., Danielson, S. L., Collins, E., & Cushing, D. (2021). Changes in diversity and species composition across multiple assemblages in the eastern Chukchi Sea during two contrasting years are consistent with borealization. *Oceanography*, *34*(2).
<https://doi.org/10.5670/oceanog.2021.213>
- Oppel, S., Dickson, D. L., & Powell, A. N. (2009). International importance of the eastern Chukchi Sea as a staging area for migrating king eiders. *Polar Biology*, *32*(5), 775–783.
<https://doi.org/10.1007/s00300-008-0580-3>
- Pickart, R. S., Spall, M. A., Lin, P., Bahr, F., McRaven, L. T., Arrigo, K. R., & Grebmeier, J. M. (2021). Physical controls on the macrofaunal benthic biomass in Barrow Canyon, Chukchi Sea. *Journal of Geophysical Research: Oceans*, *126*(5).
<https://doi.org/10.1029/2020JC017091>
- Rand, K., Logerwell, E., Bluhm, B., Chenelot, H., Danielson, S. L., Iken, K., & Sousa, L. (2018). Using biological traits and environmental variables to characterize two Arctic epibenthic invertebrate communities in and adjacent to Barrow Canyon. *Deep Sea Research Part II: Topical Studies in Oceanography*, *152*, 154–169.
<https://doi.org/10.1016/j.dsr2.2017.07.015>
- Smith, M. A., Walker, N. J., Free, C. M., Kirchhoff, M. J., Drew, G. S., Warnock, N., & Stenhouse, I. J. (2014). Identifying marine important bird areas using at-sea survey data. *Biological Conservation*, *172*, 180–189.
<https://doi.org/https://doi.org/10.1016/j.biocon.2014.02.039>
- Stabeno, P. J., Bell, S., Cheng, W., Danielson, S. L., Kachel, N. B., & Mordy, C. W. (2016). Long-term observations of Alaska Coastal Current in the northern Gulf of Alaska. *Deep Sea Research Part II: Topical Studies in Oceanography*, *132*, 24–40.
<https://doi.org/10.1016/j.dsr2.2015.12.016>
- Stabeno, P. J., Kachel, N., Ladd, C., & Woodgate, R. A. (2018). Flow patterns in the Eastern Chukchi Sea: 2010–2015. *Journal of Geophysical Research: Oceans*, *123*(2), 1177–1195.
<https://doi.org/10.1002/2017JC013135>
- Timmermans, M., & Marshall, J. (2020). Understanding Arctic Ocean circulation: A review of ocean dynamics in a changing climate. *Journal of Geophysical Research: Oceans*, *125*(4).
<https://doi.org/10.1029/2018JC014378>
- Wood, K. R., Bond, N. A., Danielson, S. L., Overland, J. E., Salo, S. A., Stabeno, P. J., & Whitefield, J. (2015). A decade of environmental change in the Pacific Arctic region. *Progress in Oceanography*, *136*, 12–31. <https://doi.org/10.1016/j.pocean.2015.05.005>

Master Reference List

- Amante, C., & Eakins, B. W. (2009). NOAA Technical Memorandum NESDIS NGDC-24 ETOPO1 1 ARC-minute global relief model: procedures, data sources and analysis. <https://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/docs/ETOPO1.pdf>
- Armitage, T. W. K., Manucharyan, G. E., Petty, A. A., Kwok, R., & Thompson, A. F. (2020). Enhanced eddy activity in the Beaufort Gyre in response to sea ice loss. *Nature Communications*, *11*(1). <https://doi.org/10.1038/s41467-020-14449-z>
- Bethoney, N. D., & Stokesbury, K. D. E. (2018). Methods for image-based surveys of benthic macroinvertebrates and their habitat exemplified by the drop camera survey for the Atlantic sea scallop. *Journal of Visualized Experiments*, *137*. <https://doi.org/10.3791/57493>
- Bluhm, B. A., & Gradinger, R. (2008). Regional variability in food availability for Arctic marine mammals. *Ecological Applications*, *18*(sp2), S77–S96. <https://doi.org/10.1890/06-0562.1>
- Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F. J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., & Olsen, M. S. (2019). Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters*, *14*(4). <https://doi.org/10.1088/1748-9326/aafc1b>
- Carmack, E., & Wassmann, P. (2006). Food webs and physical–biological coupling on pan-Arctic shelves: Unifying concepts and comprehensive perspectives. *Progress in Oceanography*, *71*(2–4), 446–477. <https://doi.org/10.1016/j.pocean.2006.10.004>
- Cazenave, F., Kercy, C., Risi, M., & Haddock, S. H. D. (2014). SeeStar: A low-cost, modular and open-source camera system for subsea observations. *2014 Oceans - St. John's*, 1–7. <https://doi.org/10.1109/OCEANS.2014.7003077>
- Chen, C.-T. A., & Borges, A. V. (2009). Reconciling opposing views on carbon cycling in the coastal ocean: Continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO₂. *Deep Sea Research Part II: Topical Studies in Oceanography*, *56*(8–10), 578–590. <https://doi.org/10.1016/j.dsr2.2009.01.001>
- Clarke, J., Moore, S., & Johnson, M. (1993). Observations on beluga fall migration in the Alaskan Beaufort Sea, 1982–87, and Northeastern Chukchi Sea, 1982–91. *Report to the International Whaling Commission*, *43*, 387.
- Clayton, L., & Dennison, G. (2017). Inexpensive video drop-camera for surveying sensitive benthic habitats: applications from glass sponge (Hexactinellida) reefs in Howe Sound,

British Columbia. *The Canadian Field-Naturalist*, 131(1), 46–54.
<https://doi.org/10.22621/cfn.v131i1.1783>

- Coachman, L. K., Aagaard, K., & Tripp, R. B. (1975). *Bering Strait: The regional physical oceanography*. University of Washington Press.
- Cooper, L. W., & Grebmeier, J. M. (2022). A chlorophyll biomass time-series for the Distributed Biological Observatory in the context of seasonal sea ice declines in the Pacific Arctic region. *Geosciences* 2022, 12, 307.
<https://doi.org/https://doi.org/10.3390/geosciences120803077>
- Cooper, L. W., Guarinello, M. L., Grebmeier, J. M., Bayard, A., Lovvorn, J. R., North, C. A., & Kolts, J. M. (2019). A video seafloor survey of epibenthic communities in the Pacific Arctic including Distributed Biological Observatory stations in the northern Bering and Chukchi seas. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 164–179. <https://doi.org/10.1016/j.dsr2.2019.05.003>
- Cooper, L. W., Larsen, I. L., Grebmeier, J. M., & Moran, S. B. (2005). Detection of rapid deposition of sea ice-rafted material to the Arctic Ocean benthos using the cosmogenic tracer ^7Be . *Deep Sea Research Part II: Topical Studies in Oceanography*, 52(24–26), 3452–3461. <https://doi.org/10.1016/j.dsr2.2005.10.011>
- Danielson, S. L., Eisner, L., Ladd, C., Mordy, C., Sousa, L., & Weingartner, T. J. (2017). A comparison between late summer 2012 and 2013 water masses, macronutrients, and phytoplankton standing crops in the northern Bering and Chukchi Seas. *Deep Sea Research Part II: Topical Studies in Oceanography*, 135, 7–26.
<https://doi.org/10.1016/j.dsr2.2016.05.024>
- Danielson, S. L., Grebmeier, J. M., Iken, K., Berchok, C., Britt, L., Dunton, K., Eisner, L., Farley, E., Fujiwara, A., Hauser, D., Itoh, M., Kikuchi, T., Kotwicki, S., Kuletz, K., Mordy, C., Nishino, S., Peralta-Ferriz, C., Pickart, R., Stabeno, P. J., ... Woodgate, R. A. (2022). Monitoring Alaskan Arctic Shelf ecosystems through collaborative observation networks. *Oceanography*. <https://doi.org/10.5670/oceanog.2022.119>
- Danielson, S. L., Hennon, T. D., Hedstrom, K. S., Pnyushkov, A., Polyakov, I., Carmack, E., Filchuk, K., Janout, M., Makhotin, M., Williams, W. J., & Padman, L. (2020). Oceanic routing of wind-sourced energy along the Arctic continental shelves. *Frontiers in Marine Science*, 7. <https://doi.org/10.3389/fmars.2020.00509>
- Danielson, S. L., Weingartner, T. J., Aagaard, K., Zhang, J., & Woodgate, R. A. (2012). Circulation on the central Bering Sea shelf, July 2008 to July 2010. *Journal of Geophysical Research: Oceans*, 117(C10),. <https://doi.org/10.1029/2012JC008303>

- de Mendonça, S. N., & Metaxas, A. (2021). Comparing the performance of a remotely operated vehicle, a drop camera, and a trawl in capturing deep-sea epifaunal abundance and diversity. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.631354>
- Dunton, K. H., Goodall, J. L., Schonberg, S. v., Grebmeier, J. M., & Maidment, D. R. (2005). Multi-decadal synthesis of benthic–pelagic coupling in the western arctic: Role of cross-shelf advective processes. *Deep Sea Research Part II: Topical Studies in Oceanography*, 52(24–26), 3462–3477. <https://doi.org/10.1016/j.dsr2.2005.09.007>
- Filbee-Dexter, K., Wernberg, T., Fredriksen, S., Norderhaug, K. M., & Pedersen, M. F. (2019). Arctic kelp forests: Diversity, resilience and future. *Global and Planetary Change*, 172, 1–14. <https://doi.org/10.1016/j.gloplacha.2018.09.005>
- Frey, K. E., Comiso, J. C., Cooper, L. W., Grebmeier, J. M., & Stock, L. v. (2021). Arctic Ocean primary productivity: The response of marine algae to climate warming and sea ice decline. *Arctic Report Card*. <https://doi.org/10.25923/kxhb-dw16>
- Gaffey, C. B., Frey, K. E., Cooper, L. W., & Grebmeier, J. M. (2022). Phytoplankton bloom stages estimated from chlorophyll pigment proportions suggest delayed summer production in low sea ice years in the northern Bering Sea. *PLOS ONE*, 17(7), e0267586. <https://doi.org/10.1371/journal.pone.0267586>
- Garrison, G. R., & Becker, P. (1976). The Barrow submarine Canyon: A drain for the Chukchi Sea. *Journal of Geophysical Research*, 81(24), 4445–4453. <https://doi.org/10.1029/JC081i024p04445>
- Goethel, C. L., Grebmeier, J. M., & Cooper, L. W. (2019). Changes in abundance and biomass of the bivalve *Macoma calcarea* in the northern Bering Sea and the southeastern Chukchi Sea from 1998 to 2014, tracked through dynamic factor analysis models. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 127–136. <https://doi.org/10.1016/j.dsr2.2018.10.007>
- Goldsmith, J., Schlegel, R. W., Filbee-Dexter, K., MacGregor, K. A., Johnson, L. E., Mundy, C. J., Savoie, A. M., McKindsey, C. W., Howland, K. L., & Archambault, P. (2021). Kelp in the eastern Canadian Arctic: Current and future predictions of habitat suitability and cover. *Frontiers in Marine Science*, 18. <https://doi.org/10.3389/fmars.2021.742209>
- Gong, D., & Pickart, R. S. (2015). Summertime circulation in the eastern Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 118, 18–31. <https://doi.org/10.1016/j.dsr2.2015.02.006>
- Graf, G., & Rosenberg, R. (1997). Bioresuspension and biodeposition: a review. *Journal of Marine Systems*, 11(3–4), 269–278. [https://doi.org/10.1016/S0924-7963\(96\)00126-1](https://doi.org/10.1016/S0924-7963(96)00126-1)

- Grebmeier, J. M. (2012). Shifting patterns of life in the Pacific Arctic and sub-Arctic Seas. *Annual Review of Marine Science*, 4, 63–78. <https://doi.org/10.1146/annurev-marine-120710-100926>
- Grebmeier, J. M., Bluhm, B. A., Cooper, L. W., Danielson, S. L., Arrigo, K. R., Blanchard, A. L., Clarke, J. T., Day, R. H., Frey, K. E., Gradinger, R. R., Kędra, M., Konar, B., Kuletz, K. J., Lee, S. H., Lovvorn, J. R., Norcross, B. L., & Okkonen, S. R. (2015). Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. *Progress in Oceanography*, 136, 92–114. <https://doi.org/10.1016/j.pocean.2015.05.006>
- Grebmeier, J. M., & Cooper, L. W. (2020). Benthic macroinfaunal and dominant taxa samples collected from Northern Bering Sea to Chukchi Sea, 1970-2017. In *Arctic Data Center*. <https://doi.org/10.18739/A2SX6499X>.
- Grebmeier, J. M., Frey, K., Cooper, L., & Kędra, M. (2018). Trends in benthic macrofaunal populations, seasonal sea ice persistence, and bottom water temperatures in the Bering Strait region. *Oceanography*, 31(2). <https://doi.org/10.5670/oceanog.2018.224>
- Grebmeier, J. M., & McRoy, P. C. (1989). Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. III. Benthic food supply and carbon cycling. *Marine Ecology Progress Series*, 53(1), 79–91. <http://www.jstor.org/stable/24834380>
- Grebmeier, J. M., Moore, S. E., Cooper, L. W., & Frey, K. E. (2019). The Distributed Biological Observatory: A change detection array in the Pacific Arctic – An introduction. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 1–7. <https://doi.org/10.1016/j.dsr2.2019.05.005>
- Grebmeier, J. M., Moore, S. E., Overland, J. E., Frey, K. E., & Gradinger, R. (2010). Biological response to recent Pacific Arctic sea ice retreats. *Eos, Transactions American Geophysical Union*, 91(18), 161. <https://doi.org/10.1029/2010EO180001>
- Grebmeier, J. M., Overland, J. E., Moore, S. E., Farley, E. V., Carmack, E. C., Cooper, L. W., Frey, K. E., Helle, J. H., McLaughlin, F. A., & McNutt, S. L. (2006). A major ecosystem shift in the northern Bering Sea. *Science*, 311(5766), 1461–1464. <https://doi.org/10.1126/science.1121365>
- Hansson, H. G. (2001). Echinodermata. In M. J. Costello, C. Emblow, & R. J. White (Eds.), *European register of marine species: a check-list of the marine species in Europe and a bibliography of guides to their identification* (Vol. 50, pp. 336–351). Collection Patrimoines Naturels.
- Hauser, D. D. W., Laidre, K. L., Stern, H. L., Suydam, R. S., & Richard, P. R. (2018). Indirect effects of sea ice loss on summer-fall habitat and behaviour for sympatric populations of an

- Arctic marine predator. *Diversity and Distributions*, 24(6), 791–799.
<https://doi.org/10.1111/ddi.12722>
- Hennon, T. D., Danielson, S. L., Woodgate, R. A., Irving, B., Stockwell, D. A., & Mordy, C. W. (2022). Mooring measurements of Anadyr Current nitrate, phosphate, and silicate enable updated Bering Strait nutrient flux estimates. *Geophysical Research Letters*, 49(16).
<https://doi.org/10.1029/2022GL098908>
- Hill, V., & Cota, G. (2005). Spatial patterns of primary production on the shelf, slope and basin of the Western Arctic in 2002. *Deep Sea Research Part II: Topical Studies in Oceanography*, 52(24–26), 3344–3354. <https://doi.org/10.1016/j.dsr2.2005.10.001>
- Hill, V. J., Matrai, P. A., Olson, E., Suttles, S., Steele, M., Codispoti, L. A., & Zimmerman, R. C. (2013). Synthesis of integrated primary production in the Arctic Ocean: II. In situ and remotely sensed estimates. *Progress in Oceanography*, 110, 107–125.
<https://doi.org/10.1016/j.pocean.2012.11.005>
- Iken, K., Mueter, F., Grebmeier, J. M., Cooper, L. W., Danielson, S. L., & Bluhm, B. A. (2019). Developing an observational design for epibenthos and fish assemblages in the Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 162, 180–190.
<https://doi.org/10.1016/j.dsr2.2018.11.005>
- Jay, C., Fischbach, A., & Kochnev, A. (2012). Walrus areas of use in the Chukchi Sea during sparse sea ice cover. *Marine Ecology Progress Series*, 468, 1–13.
<https://doi.org/10.3354/meps10057>
- Krumbein, W. C. (1934). Size frequency distributions of sediments. *SEPM Journal of Sedimentary Research*, Vol. 4. <https://doi.org/10.1306/D4268EB9-2B26-11D7-8648000102C1865D>
- Levine, J. M., & HilleRisLambers, J. (2009). The importance of niches for the maintenance of species diversity. *Nature*, 461(7261), 254–257. <https://doi.org/10.1038/nature08251>
- Longley, W. H., & Martin, C. (1927). The first autochromes from the ocean bottom. *National Geographic*, 12–13.
- Lu, X., Xu, J., Xu, Z., & Liu, X. (2021). Assessment of benthic ecological quality status using multi-biotic indices based on macrofaunal assemblages in a semi-enclosed bay. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.734710>
- Madsen, FJ., & Hansen, B. (1994). Echinodermata Holothurioidea. *Marine Invertebrates of Scandinavia*, 9(1), 143. <https://www.marinespecies.org/aphia.php?p=sourcedetails&id=662>
- Moore, S. E., Logerwell, E., Eisner, L., Farley, E. v., Harwood, L. A., Kuletz, K., Lovvorn, J., Murphy, J. R., & Quakenbush, L. T. (2014). Marine fishes, birds and mammals as sentinels

- of ecosystem variability and reorganization in the Pacific Arctic region. In *The Pacific Arctic Region* (pp. 337–392). Springer Netherlands. https://doi.org/10.1007/978-94-017-8863-2_11
- Mountain, D. G., Coachman, L. K., & Aagaard, K. (1976). On the flow through Barrow Canyon. *Journal of Physical Oceanography*, *6*(4), 461–470. [https://doi.org/10.1175/1520-0485\(1976\)006<0461:OTFTBC>2.0.CO;2](https://doi.org/10.1175/1520-0485(1976)006<0461:OTFTBC>2.0.CO;2)
- Mueter, F., Iken, K., Cooper, L., Grebmeier, J. M., Kuletz, K., Hopcroft, R., Danielson, S. L., Collins, E., & Cushing, D. (2021). Changes in diversity and species composition across multiple assemblages in the eastern Chukchi Sea during two contrasting years are consistent with borealization. *Oceanography*, *34*(2). <https://doi.org/10.5670/oceanog.2021.213>
- Nelson, R. J., Ashjian, C. J., Bluhm, B. A., Conlan, K. E., Gradinger, R. R., Grebmeier, J. M., Hill, V. J., Hopcroft, R. R., Hunt, B. P. v., Joo, H. M., Kirchman, D. L., Kosobokova, K. N., Lee, S. H., Li, W. K. W., Lovejoy, C., Poulin, M., Sherr, E., & Young, K. V. (2014). Biodiversity and biogeography of the lower trophic taxa of the Pacific Arctic region: sensitivities to climate change. In *The Pacific Arctic Region* (pp. 269–336). Springer Netherlands. https://doi.org/10.1007/978-94-017-8863-2_10
- Nolan, K. A., & Callahan, J. E. (2006). Beachcomber Biology: The Shannon-Weiner species diversity index. *Tested Studies for Laboratory Teaching*, *27*, 334–338. https://www.ableweb.org/biologylabs/wp-content/uploads/volumes/vol-27/22_Nolan.pdf
- Oppel, S., Dickson, D. L., & Powell, A. N. (2009). International importance of the eastern Chukchi Sea as a staging area for migrating king eiders. *Polar Biology*, *32*(5), 775–783. <https://doi.org/10.1007/s00300-008-0580-3>
- Peterson, B. J., Holmes, R. M., McClelland, J. W., Vörösmarty, C. J., Lammers, R. B., Shiklomanov, A. I., Shiklomanov, I. A., & Rahmstorf, S. (2002). Increasing river discharge to the Arctic Ocean. *Science*, *298*(5601), 2171–2173. <https://doi.org/10.1126/science.1077445>
- Peterson, B. J., McClelland, J., Curry, R., Holmes, R. M., Walsh, J. E., & Aagaard, K. (2006). Trajectory shifts in the Arctic and Subarctic freshwater cycle. *Science*, *313*(5790), 1061–1066. <https://doi.org/10.1126/science.1122593>
- Pickart, R. S., Spall, M. A., Lin, P., Bahr, F., McRaven, L. T., Arrigo, K. R., & Grebmeier, J. M. (2021). Physical controls on the macrofaunal benthic biomass in Barrow Canyon, Chukchi Sea. *Journal of Geophysical Research: Oceans*, *126*(5). <https://doi.org/10.1029/2020JC017091>

- Rand, K., Logerwell, E., Bluhm, B., Chenelot, H., Danielson, S. L., Iken, K., & Sousa, L. (2018). Using biological traits and environmental variables to characterize two Arctic epibenthic invertebrate communities in and adjacent to Barrow Canyon. *Deep Sea Research Part II: Topical Studies in Oceanography*, 152, 154–169. <https://doi.org/10.1016/j.dsr2.2017.07.015>
- Reynolds, O. (1883). An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Philosophical Transactions of the Royal Society of London*, 174, 935–982. <https://doi.org/10.1098/rstl.1883.0029>
- Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, M., Pietzsch, T., Preibisch, S., Rueden, C., Saalfeld, S., Schmid, B., Tinevez, J.-Y., White, D. J., Hartenstein, V., Eliceiri, K., Tomancak, P., & Cardona, A. (2012). Fiji: an open-source platform for biological-image analysis. *Nature Methods*, 9(7), 676–682. <https://doi.org/10.1038/nmeth.2019>
- Sebens, K., Sarà, G., & Nishizaki, M. (2017). Energetics, particle capture, and growth dynamics of benthic suspension feeders. In *Marine Animal Forests* (pp. 1–42). Springer International Publishing. https://doi.org/10.1007/978-3-319-17001-5_17-3
- Smith, M. A., Walker, N. J., Free, C. M., Kirchhoff, M. J., Drew, G. S., Warnock, N., & Stenhouse, I. J. (2014). Identifying marine important bird areas using at-sea survey data. *Biological Conservation*, 172, 180–189. <https://doi.org/https://doi.org/10.1016/j.biocon.2014.02.039>
- Snelgrove, P. V. R. (1998). The biodiversity of macrofaunal organisms in marine sediments. *Biodiversity and Conservation*, 7(9), 1123–1132. <https://doi.org/10.1023/A:1008867313340>
- Solé, A., Mas, J., & Esteve, I. (2007). A new method based on image analysis for determining cyanobacterial biomass by CLSM in stratified benthic sediments. *Ultramicroscopy*, 107(8), 669–673. <https://doi.org/10.1016/j.ultramic.2007.01.007>
- Stabeno, P. J., Bell, S., Cheng, W., Danielson, S. L., Kachel, N. B., & Mordy, C. W. (2016). Long-term observations of Alaska Coastal Current in the northern Gulf of Alaska. *Deep Sea Research Part II: Topical Studies in Oceanography*, 132, 24–40. <https://doi.org/10.1016/j.dsr2.2015.12.016>
- Stabeno, P. J., Kachel, N., Ladd, C., & Woodgate, R. A. (2018). Flow Patterns in the eastern Chukchi Sea: 2010–2015. *Journal of Geophysical Research: Oceans*, 123(2), 1177–1195. <https://doi.org/10.1002/2017JC013135>

- Stöhr, S., O'Hara, T., & Thuy, B. (2022). World Ophiuroidea database. Ophiuroidea. *World Register of Marine Species*.
<https://www.marinespecies.org/aphia.php?p=taxdetails&id=123084> on 2022-06-15
- Timmermans, M. L., & Marshall, J. (2020). Understanding Arctic Ocean circulation: a review of ocean dynamics in a changing climate. *Journal of Geophysical Research: Oceans*, *125*(4).
<https://doi.org/10.1029/2018JC014378>
- Waga, H., Eicken, H., Hirawake, T., & Fukamachi, Y. (2021). Variability in spring phytoplankton blooms associated with ice retreat timing in the Pacific Arctic from 2003–2019. *PLOS ONE*, *16*(12), e0261418. <https://doi.org/10.1371/journal.pone.0261418>
- Weingartner, T. J., Aagaard, K., Woodgate, R. A., Danielson, S. L., Sasaki, Y., & Cavalieri, D. (2005). Circulation on the north central Chukchi Sea shelf. *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(24–26), 3150–3174.
<https://doi.org/10.1016/j.dsr2.2005.10.015>
- Weingartner, T. J., Cavalieri, D., Aagaard, K., & Sasaki, Y. (1998). Circulation, dense water formation, and outflow on the northeast Chukchi shelf. *Journal of Geophysical Research*, *103*, 7647–7661.
- Wood, K. R., Bond, N. A., Danielson, S. L., Overland, J. E., Salo, S. A., Stabeno, P. J., & Whitefield, J. (2015). A decade of environmental change in the Pacific Arctic region. *Progress in Oceanography*, *136*, 12–31. <https://doi.org/10.1016/j.pocean.2015.05.005>
- Woodgate, R. A. (2018). Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data. *Progress in Oceanography*, *160*, 124–154.
<https://doi.org/10.1016/j.pocean.2017.12.007>
- Woodgate, R. A., Aagaard, K., & Weingartner, T. J. (2005). A year in the physical oceanography of the Chukchi Sea: Moored measurements from autumn 1990–1991. *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(24–26), 3116–3149.
<https://doi.org/10.1016/j.dsr2.2005.10.016>
- Woodgate, R. A., & Peralta-Ferriz, C. (2021). Warming and freshening of the Pacific inflow to the Arctic from 1990-2019 implying dramatic shoaling in Pacific winter water ventilation of the Arctic Water column. *Geophysical Research Letters*, *48*(9).
<https://doi.org/10.1029/2021GL092528>