USING A GEOGRAPHICAL INFORMATION SYSTEM APPROACH TO ASSESS SEA ICE IMPACTS ON A PRODUCTIVE BENTHIC SYSTEM IN THE NORTHERN BERING SEA

To the Graduate Council:

I am submitting herewith a thesis written by Jaclyn Leigh Clement entitled "Using a geographical information system approach to assess sea ice impacts on a productive benthic system in the northern Bering Sea." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degreee of Master of Science, with a major in Ecology and Evolutionary Biology.

Jacqueline Grebmeier, Major Professor

We have read this thesis and recommend its acceptance:

Acceptance for the Council:

Vice Provost and Dean of Graduate Studies

USING A GEOGRAPHICAL INFORMATION SYSTEM APPROACH TO ASSESS SEA ICE IMPACTS ON A PRODUCTIVE BENTHIC SYSTEM IN THE NORTHERN BERING SEA

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jaclyn Leigh Clement
August 2002

Acknowledgements

I would like to thank Dr. Jacqueline Grebmeier for her endless expertise, enthusiasm, and encouragement. I would also like to thank Dr. Lee Cooper for guidance in a number of different aspects of this work from the ship to print. Dr. Grebmeier and Dr. Cooper provided the opportunity for this research as well as a significant amount of their previously collected data. Dr. Shih-Lung Shaw provided GIS expertise and direction. For insightful and thought-provoking comments, I would like to thank Dr. James Drake. A significant amount of laboratory assistance and emotional support was provided by Becky Brown, Arianne Balsom, Rebecca Levy, Kim Harmon, Jim Bartlett, Holly Kelly, and Kathie Stevens. I would also like to thank the Captain and crew of the USCGC Polar Star, USCGC Polar Sea, and RV Alpha Helix. Finally, a most special thanks to my parents, Randy and Lana Clement, for providing me with love and encouragement.

Abstract

Physical, hydrochemical, and biological data were collected during three research cruises from winter through spring in the northern Bering Sea. In addition, seasonal ice cover data were used to evaluate the relationship between ice and specific biological processes. Ice-water-biotic interactions were investigated and possible relationships defined. Data collected during late winter indicate low levels of water column production and benthic respiration. However, spring measurements made during and just after ice-melt indicate a time of high water column production and benthic respiration. Interannual variation in the spatial and temporal distribution of sea ice affects the timing of seasonal processes, particularly the onset of spring production. In this study, seasonally light ice coverage was followed by temporally accelerated water column production events. Variation in ice cover also seems to be important in influencing sea surface temperature, with an early increase following a season of reduced ice cover. These changes in seasonal processes could have potentially far-reaching effects on the northern Bering Sea ecosystem.

A carbon flux model was created for describing the annual carbon production and benthic carbon consumption cycle in an area south of St. Lawrence Island in the Bering Sea. Model output gives an annual carbon productivity of 390 g C m^{-2} yr^{-1} and an annual benthic consumption of 45.73 g C m^{-2} yr^{-1}. These values are consistent with previous work in nearby regions of the Bering and Chukchi Seas.

Table of Contents

Page

I. Introduction 1

II. Winter ice conditions: A comparison between 1999 and 2001 7

A. Introduction 7

B. Methods 10

C. Results 15

D. Discussion and conclusions 34

III. Sea ice influence on water column and benthic processes: The transition from winter to spring 39

A. Introduction 39

B. Methods 41

C. Results 43

D. Discussion and conclusions 52

IV. Carbon flux model 57

A. Introduction 57

B. Methods 57

C. Results 59

D. Discussion and conclusions 62

V. Conclusions and summary 66

List of References 69

Appendix 80

Vita 89

List of Tables

Table Page

1. Data sources used in ice map preparation during 1999 and 2001 13
2. Wilcoxon signed rank test results for differences in various parameters measured at 30 reoccupied stations in 1999 and 2001 28
3. Spearman's rho correlations between benthic macrofauna organic carbon biomass and environmental parameters during all three cruises 53
4. Spearman's rho correlations between sediment oxygen respiration and environmental parameters during all three cruises 54
5. Carbon flux model seasonal assumptions and cruise data used to derive seasonal averages 58
6. Daily, seasonal, and seasonal percent of annual estimated carbon production 63
7. Daily, seasonal, and seasonal percent of annual estimated benthic carbon consumption 64

List of Figures

Figure Page

1. Stations locations for three cruises 6
2. Sea ice formation during 1999 and 2001 16
3. Sea ice-melt during 1999 and 2001 17
4. Wind direction during February 2001 recorded at 57.08°N, 177.78°W by a NOAA data collection buoy 19
5. Wind direction during February 2001 recorded at Nome, AK 20
6. Winter ice thickness during 1999 and 2001 22
7. Spring ice thickness during 1999 and 2001 23
8. Bottom water salinity in April 1999 25
9. Bottom water salinity in March-April 2001 26
10. Bottom water salinity comparison between 1999 and 2001 29
11. Station locations during April 1999 and March-April 2001 30
12. Bottom water temperature in March-April 2001 31
13. T/S plot during March-April 2001 32
14. Integrated water column chlorophyll-*a* for three cruises 33
15. Organic carbon benthic macrofaunal biomass for three cruises 35
16. Ice concentration on May 11, 1994 44
17. Ice concentration on May 25, 1994 and integrated chlorophyll-*a* for stations sampled May 22-28 45
18. Ice concentration on June 1, 1994 and integrated chlorophyll-*a* for stations sampled May 29 – June 4 46

Figure Page

19. Ice concentration on June 8, 1994 and integrated chlorophyll-*a* for stations sampled June 5-8 47

20. Sea surface temperature along 62°N latitude, spanning 170°W - 180° longitude during early-June 1999 and 2001 49

21. SeaWIFS satellite images of surface phytoplankton pigment concentration during spring 1999 and 2001 51

22. Schematic diagram of stocks, flow, and converters 60

23. Carbon flux model output 61

I. Introduction

Previous work in the Bering Sea has identified an area of high benthic biomass south of St. Lawrence Island (Grebmeier et al. 1995). Marine mammals such as the Pacific walrus (*Odobenus rosmarus*; Fay et al. 1977) and the California gray whale (*Eschrichtius robustus*; Highsmith & Coyle 1992) are known to feed in this area. In addition, this region has recently been found to be an important winter feeding-ground for a threatened species of diving seaduck, the Spectacled Eider (*Somateria fischeri*; Stehn et al. 1993, Peterson et al. 1998, Peterson et al. 1999). Anadyr Water, Bering Shelf Water, and Alaska Coastal Water are three primary water masses flowing over the northern Bering Sea shelf. The Anadyr Current to the west provides the highest nutrient input into the system, while the Alaska Coastal Current to the east tends to be the most nutrient-poor (Walsh et al. 1989, Grebmeier & Cooper 1995). In addition, there is a "cold pool" of subsurface water with temperatures less than 2°C (Wyllie-Echeverria & Wooster 1998). This cold pool is variable in extent, but usually extends from Russia to Bristol Bay, AK between the 50 and 100m isobaths. The extent of winter sea ice is likely the major influence on the bottom water temperature and position of this water mass. The cold pool is important in determining the range of temperature-sensitive fish species, such as Arctic cod and walleye Pollock (Wyllie-Echeverria & Wooster 1998).

The dynamic Bering Sea ecosystem is characterized by strong seasonal cycles (Muench & Ahlnäs 1976) and a high degree of interannual variability in climate patterns (Walsh & Johnson 1979, Niebauer 1981). The seasonal cycle of sea ice begins with its formation in October or November, with ice-melt occurring from April through June (Pease 1980, Overland & Pease 1982). An important feature in this cycle is the presence of winter polynyas, or relatively ice-free areas surrounded by ice, which occur to the leeward side of all major islands and peninsulas in the Bering Sea (Muench & Ahlnäs 1976). In particular, the St. Lawrence Island polynya (SLIP) is an important site for sea ice production (Muench & Ahlnäs 1976, Stringer & Groves 1991). After considering the seasonal sea ice extent of the Northern Hemisphere for the years 1953-77, Walsh and Johnson (1979) found that the Bering Sea has the greatest standard deviation for departures from the monthly mean sea ice extent when compared with other high latitude seas (e.g. Barents, Kara, Laptev, and East Greenland Seas). In other words, monthly ice extent was more variable in the Bering Sea than any other high latitude sea. Many factors including atmospheric circulation, storm activity, sea surface temperature (SST), and air temperature contribute to the spatial and temporal distribution of ice (Pease 1980, Niebauer 1981, Overland & Pease 1982).

In addition to interannual variability, climatologists have recognized large-scale, low frequency shifts in climate patterns. Regime shifts are changes in the North Pacific climate system that occur rapidly and concomitantly with biological changes in community composition, species abundance and trophic structure (McGowan et al. 1998, Hare et al. 2000). These dramatic shifts happen abruptly, but last for long time periods, usually 10-20 years (Hare et al. 2000). Regime shifts in the Bering Sea have been associated with changes in the state of large-scale climate patterns including the Arctic Oscillation (AO), the Pacific Decadal Oscillation (PDO), and the Aleutian Low (Trenberth & Hurrell 1994, Stabeno and Overland 2001). These climate patterns control parameters such as sea surface temperature, air temperature, storm activity, and winds, which all influence the spatial and temporal distribution of sea ice (Niebauer 1981, Overland & Pease 1982).

The presence of sea ice affects the physical properties of the underlying water column by reducing light penetration, decreasing heat and gas exchange, and reducing mechanical mixing (Alexander 1981). At the same time that ice functions as a barrier between air and water, it is also a substrate for many organisms from sea ice algae to apex predators (Alexander 1981). Several species of birds and mammals use the ice as a substrate upon which they live, feed, and reproduce (e.g. ringed, bearded, spotted, and ribbon seals require ice for giving birth; Fay 1974, Alexander 1981). Moving sea ice is also used by the Pacific walrus and some seal species as transportation to feeding grounds in the Bering Sea in winter and north again through Bering Strait to the Chukchi Sea during spring (Fay 1974). While the relationship between sea ice and marine mammal distribution and biology has been well investigated, the effect of ice on the benthos is less clear. It is known that benthic organisms depend on the overlying shallow water column for food and that physical processes have a strong influence on benthic communities (Stoker 1981, Grebmeier 1987). Therefore, it is reasonable to expect changes in physical processes to be reflected in the benthos on shallow shelves.

A warming trend has been observed in the Arctic throughout the 1980's and 1990's (Grotefendt et al. 1998, Rothrock et al. 1999, Stabeno & Overland 2001). Whether this warming is due to a natural oscillation or anthropogenic global warming is still undecided. However, it is generally agreed upon that both Arctic sea ice extent and sea ice thickness have been reduced over the past 20 years (Grotefendt et al. 1998, Rothrock et al. 1999).

Recent global warming model predictions show that the greatest effects will be seen in high latitude regions, especially the Arctic and Antarctic regions during the winter period (Izrael et al. 1992, Banks & Wood 2002, Nelson et al. 2002). The Hadley Centre Model (Bershire, United Kingdom), the Parallel Climate Model (developed by the Los Alamos National Laboratory, the Naval Postgraduate School, the US Army Corps of Engineers' Cold Regions Research and Engineering Lab, and the National Center for Atmospheric Research), and a model developed by the Geophysical Fluid Dynamics Laboratory (Princeton, New Jersey) all agree that the Arctic will be highly impacted (Banks & Wood 2002, Washington et al. 2000, Weatherly & Bitz 2001, Vinnikov et al. 1999). A global warming model prediction developed by Duffy et al. (2001) shows a decrease in the vertical salinity gradient in the Southern Ocean after hundreds of years of simulation and the loss of freshwater forcing due to sea ice-melt. A warming at the poles would decrease the temperature gradient toward the equator and might potentially lead to a decrease in wind and current circulation (Voss & Mikolajewicz 2002). Decreased circulation would likely lead to reduced upwelling in the World Ocean (Izrael et al. 1992). Predictions of future primary production under global warming indicate an increase due to more conducive conditions (e.g. less ice and warmer temperatures) (Izrael et al. 1992, Rysgaard et al. 1999). In addition, a rise in sea temperature might lead to earlier spring phytoplankton blooms and a lengthening of the entire production cycle (Stabeno & Overland 2001, Hunt et al. unpubl. data).

The influence of global warming on the ecosystem is complex because several predicted simultaneous changes, including a reduction in current circulation and upwelling, could adversely affect primary production. In any event, changes in primary production would most certainly be reflected up through the food web to zooplankton grazers, benthic communities, fish populations, and apex predators. Predicted global warming enhances the importance of examining the relationship between sea ice and biological communities (Grotefendt et al. 1998).

This study provides a detailed examination of the spatial and temporal distribution of sea ice for the years of 1994, 1998-1999, and 2000-2001. In an attempt to quantify the relationship between sea ice and benthic biomass, these data will be compared to hydrological, biological, and sediment measurements taken during three research cruises from late winter through spring in the northern Bering Sea (Fig.1). The study region, located in the area of the St. Lawrence Island polynya, will be hereafter referred to as SLIP.

The fact that ice and benthic macroinvertebrates operate on different time scales complicates their relationship (e.g. ice is on a yearly cycle and benthic organisms are slow-growing, long-lived animals (Stoker 1978, Clarke 1980). However, patterns in relatively short-lived parameters, such as chlorophyll-*a*, can give an indication of the food source available to the benthos. The following questions were addressed in this study:

1. Does variation in winter ice cover characteristics affect water column and sediment parameters during winter and/or spring?
2. Does the timing of ice-melt affect water column and sediment parameters?

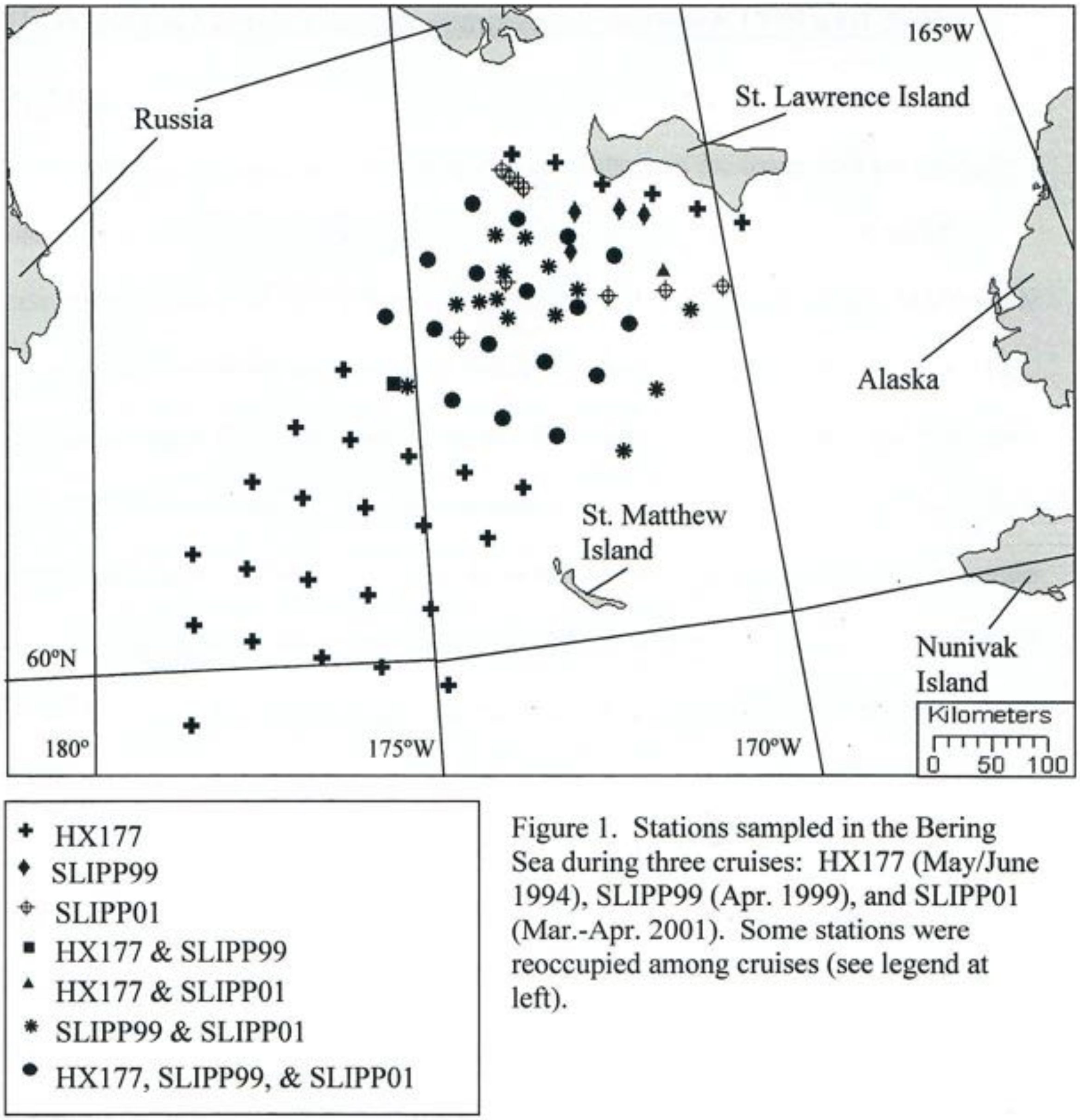


Figure 1. Stations sampled in the Bering Sea during three cruises: HX177 (May/June 1994), SLIPP99 (Apr. 1999), and SLIPP01 (Mar.-Apr. 2001). Some stations were reoccupied among cruises (see legend at left).

II. Winter ice conditions: A comparison between 1999 and 2001

A. Introduction

The Bering Sea shows a strong seasonal pattern of ice cover with ice typically present from December to June (Pease 1980, Overland & Pease 1982). A small percentage of pack ice moves from the Arctic Ocean south through Bering Strait, while the majority freezes within the Bering Sea (Pease 1980, Overland & Pease 1982). Ice formation begins along the coasts of the northern Bering Sea in October and November (Overland & Pease 1982). As winter progresses, prevailing northerly winds force the ice southward (Fay 1974, Muench & Ahlnäs 1976, Overland & Pease 1982). An important feature in this process are polynyas, or relatively open areas of water in ice-covered seas, which form typically to the south of all major peninsulas and islands in the Bering Sea including St. Lawrence Island (Overland & Pease 1982, Grebmeier & Cooper 1995). New ice is formed within these polynyas and subsequently moved south by northerly winds (Muench & Ahlnäs 1976, McNutt 1981), setting up what has been described as a conveyor belt of ice movement (Pease 1980). As ice moves southward it encounters warmer surface water and, upon reaching its thermodynamic limit, melts. This cools the surface water and allows the next southward bound ice movement to advance further.

Maximum ice extent usually occurs about 1,000 km south of Bering Strait at the shelf break near the 200m isobath (Muench & Ahlnäs 1976, Alexander 1981, Niebauer 1981). However, there is a high degree of interannual variability in the location of the ice edge. I defined a heavy ice year as one in which the ice edge reaches St. Paul Island (57.3°N, 170.3°W) or beyond. A light ice year might have a maximum extent only to St. Matthew Island (60.7°N, 172.7°W) or Nunivak Island (60.4°N, 166.5°W; Overland &

Pease 1982). Ice-melt usually begins in April (Pease 1980) and by late-June the sea is ice-free following melt and ice transport northward through Bering Strait (McRoy & Goering 1974, Overland & Pease 1982)

Many factors including atmospheric circulation, storm activity, sea surface temperature (SST), and air temperature contribute to the spatial and temporal distribution of sea ice (Niebauer 1981, Overland & Pease 1982). Atmospheric circulation is influenced by the Arctic Oscillation (AO), which has its strongest impact during winter (Stabeno & Overland 2001). The AO influences surface winds over the Northern Hemisphere due to the orientation of low and high pressure systems (Thompson & Wallace 2001). Atmospheric pressure system changes can be positive (usually associated with warmer weather) or negative (usually associated with colder weather). During the 1980's and 1990's, the AO was in a mostly positive state causing warmer temperatures in the sub-Arctic and an unusually weak Aleutian Low (Thompson and Wallace 2001). The Aleutian Low is a low pressure system usually located near the Aleutian Island chain (Overland 1981). Winter storms (centers of low pressure) are slightly more frequent and much more intense than summer storms over the southern Bering Sea (Overland 1981). These strong winter storms can inhibit the advance of sea ice (Overland & Pease 1982). Mantua et al. (1997) defined the Pacific Decadal Oscillation (PDO) as a suite of changes in Pacific climate occurring on an interdecadal scale. The PDO has its greatest impact on sea surface temperature in the North Pacific and southern Bering Sea.

Regime shifts in the Bering Sea have been associated with changes in the state of the AO, PDO, and Aleutian Low (Trenberth & Hurrell 1994, Stabeno and Overland 2001). The early- and mid-1970's were characterized by cold sea surface and air temperatures. Ice coverage was extensive over the Bering Sea shelf during these "cold years" (Stabeno and Overland 2001). In 1977, however, the AO and PDO both changed state, ushering in a new warm regime (Stabeno and Overland 2001). SST warmed after 1977 in the Bering Sea (Hare & Mantua 2000) and sea ice extent was reduced (Walsh et al. 1989, Stabeno and Overland 2001). Winter sea level pressure (SLP) data indicate an intensified Aleutian Low (Hare & Mantua 2000). Biological changes were characterized by large increases in Gulf of Alaska yields of important fish species such as sockeye and pink salmon, while crustacean yields declined. Changes in physical mechanisms regulating primary production depth and rate of vertical mixing are the likely causes of these fishery changes (Hare & Mantua 2000, McGowan et al. 1998).

There is strong biological evidence to support another regime shift in 1989 for some parts of the North Pacific (Hare & Mantua 2000). Biologically there were declines in Bering Sea groundfish recruitment, and Western Alaska chinook, chum, and pink salmon catch (Hare & Mantua 2000). In contrast, there was a marked increase in Bering Sea jellyfish biomass (Brodeur 1999, Hare & Mantua 2000). Hunt et al. (1999) noted anomalous conditions during 1997 and 1998 such as major changes in the zooplankton community, a sharp decline in short-tailed shearwaters (*Puffinus tenuirostris*), and cross-shelf advection of larval fish species. In addition, large-scale blooms of the coccolithophorid phytoplankton, *Emiliania huxleyi*, were reported during these unusually warm years (Vance et al. 1998, Hunt et al. 1999). Climatic conditions during 1989-98 did not revert to the "cold years" prior to 1976; however, there was a slight decrease in winter SST (0.2°C-0.6°C) and a minimal increase in ice cover (Hare & Mantua 2000, Stabeno and Overland 2001). In addition, lower winter mean sea level pressure (SLP) and higher summer SLP were noticed for the Arctic (Hare & Mantua 2000). A weakened winter Aleutian Low along with an intensified winter and summer Arctic vortex were characteristic of this time period (Hare & Mantua 2000).

Bering Sea climate conditions during 1999 have been described as being similar to the "cold years" prior to 1976 (e.g. negative SST and air temperature anomalies and extensive ice coverage; Radchenko 2001). While it is too soon to have a complete description of climatic conditions during 2001, this study shows that ice coverage was greatly reduced. In this chapter, I examine ice characteristics during 1999 and 2001 in relation to water column, sediment, and biological measurements made during April 1999 and March-April 2001.

B. Methods

In this study, I undertook a retrospective analysis of sea ice conditions in the Bering Sea using data available from the U.S. National Ice Center, Washington D.C. In addition, physical, hydrochemical, and biological oceanographic data were analyzed from collections made in 1994, 1999 and 2001 as part of a multi-year, interdisciplinary study under the direction of Drs. JM Grebmeier and LW Cooper (Cooper et al. 2002, Grebmeier and Dunton 2000, Grebmeier and Cooper 1995, Grebmeier et al. 1990, and unpublished data). Appendices A, B, and C show station information for cruises SLIPP01, SLIPP99, and HX177 respectively. In this chapter, I compare ice and field data between 1999 and 2001. In the following chapter, I will utilize ice and field data from 1994, 1999, and 2001 in order to examine the transition from winter to spring.

1. Ice data for 1998-2001

Ice maps were downloaded from the National Ice Center website (www.natice.noaa.gov) in interchange file format (.e00). ArcExplorer 1.1 Import Utility (ESRI®, Inc., Redlands, CA) was used to convert each map from interchange file format to the ESRI® ArcInfo coverage format. All ice-related maps are in Polar Stereographic projection with 60°N as the latitude of true scale. Polar Stereographic is a conformal projection, which preserves shape, thus distance measurements may be distorted.

A specific ice coverage code field was attached to attributes within these files. The resultant polygon coverage was associated with an attribute table containing a field entitled "Ice Code". The Ice Code field contained codes for ice concentration, ice thickness, and stage of development (e.g. new, brash ice, etc). A new field was created in the attribute table and an ice concentration value for each polygon was taken from the Ice Code field and entered into a new field entitled "Ice Concentration". A new field for ice thickness was created from the Ice Code field using a similar process. Each ice map was checked against the original "Egg Code" map from which it was digitized. (Egg Code maps are representations of sea ice coverage, condition, and state of development using numerical codes that are placed within oval symbols on National Ice Center sea ice coverage maps.) All discrepancies between the values of the Ice Code field in the digitized maps and the values in the Egg Code maps were changed to match the original Egg Code values, so all explicit and implicit errors present in the original Egg Code values remain in the analyses I accomplished. Each Egg Code map was created from one or more sources of information with various spatial resolutions. The sources include Radarsat (Radar Satellite), OLS (Operational Linescan System), AVHRR (Advanced

Very High Resolution Radiometer), and estimation from a combination of climatology and meteorology. Metadata was available for each map including the percentage of each source that was used in map production. The percentage of each source used in map preparation was recorded for each map used in this study. Average percentages were calculated from these recordings. The breakdown of the percentage of each data source used in map preparation is shown in Table 1 with the majority of data coming from satellite information.

2. Field data

Physical, hydrochemical, and biological data were collected on all cruises being evaluated in this study and the methods for these collections are outlined below (see Cooper et al. 2002 for further description of methodology).

a. Bottom water salinity, bottom water sigma-t, surface water temperature, bottom water temperature, and depth:

Hydrographic measurements were made using a conductivity-temperature-depth (CTD) profiler with an attached rosette of water collection bottles.

b. Water column chlorophyll-*a*:

Seawater samples (250 mL subsamples) were collected from Niskin bottles attached to a CTD/Rosette at several representative depths over the entire water column. Samples were filtered using Whatman GF/C filters and extracted in 10 mL of 90% acetone. After a 24-hour refrigerated extraction period, the chlorophyll-*a* (chl-*a*) concentration was measured using a Turner Designs AU-10 fluorometer. At all times, water samples, filters, and acetone extract were kept in the dark as much as possible so as

Table 1. The percentage of each data source used in map preparation averaged over maps used during 1998-1999, maps used during 2000-2001, and maps used during 1998-2001 (all maps combined).

Data Source	1998-1999	2000-2001	All maps combined
Radarsat	37.4%	70.6%	51.1%
OLS	14.7%	13.5%	14.2%
AVHRR	27.3%	2.1%	16.9%
Estimated	20.5%	13.8%	17.8%

not to affect chl-*a* concentrations. Bottom water chl-*a* is the concentration at the deepest bottle depth, in most cases, within 5-10 m of the bottom. Integrated chl-*a* was calculated by averaging the concentration at adjacent depths and multiplying by the depth difference in each pair of adjacent depths. Finally, all values are summed to give total integrated water column chl-*a* mg m^{-2}.

c. Sediment chlorophyll-*a*:

One cm^3 of surface sediment was collected from the van Veen grab prior to its opening using a modified syringe. The sediment was placed in a centrifuge tube along with 10mL of 90% acetone. To ensure extraction of all chl-*a*, tubes were refrigerated for 12 hours in the dark and the mass of chl-*a* associated with that 1 cm^3 of surface sediment was measured with the Turner Designs AU-10 fluorometer. Two sediment chl-*a* samples were taken at each station and the mean of the two is reported here in units of chl-*a* mg m^{-2} of surface sediments.

d. Benthic biomass:

Four replicate benthic samples were obtained at each station with a 0.1m^2 van Veen grab weighing 88.7 kg including 32 kg lead weight. Each sample was placed on a screen with mesh size of 1-mm and washed with seawater to remove sediment. Samples were preserved in a 10% seawater formalin solution for later laboratory analysis. In the laboratory, organisms were keyed to family level, except for dominant bivalves, which were keyed to genus or species for another part of the main study, which will not be reported here. To obtain wet weight measurements, organisms were blotted dry and then weighed on a calibrated scale. Previously verified carbon conversion values were used to convert wet-weight values to organic carbon biomass (Stoker 1978, Grebmeier 1987).

The use of organic carbon values removes the influence of calcium carbonate in mollusks and echinoids (Grebmeier & Cooper 1995).

e. Statistics:

The Wilcoxon Signed Rank Test, a nonparametric, paired comparison test, was applied to data recorded at the 30 reoccupied stations between the two cruises. The purpose of this test was to identify differences in the means of various parameters measured during cruises in 1999 and 2001. I chose a nonparametric test for all data analysis because the data was not normally distributed and sample sizes were low.

C. Results

Ice concentration and ice thickness were evaluated on a weekly basis from December through June 1998-1999 and 2000-20001. Field data collection included 36 stations in April 1999 and 42 stations in March-April 2001. Thirty stations were reoccupied between the years and were used in paired comparisons.

1. Sea ice advance and retreat

The time periods of 1998-99 and 2000-01 were very different in terms of ice extent, coverage, and thickness over both temporal and spatial scales. During early winter of 1998, ice formed quickly and advanced southward reaching St. Lawrence Island by mid-December. Ice concentration was 90-100% for the period of mid-January to early-May 1999 for most of the region south of Bering Strait to St. Matthew Island (Figs. 2, 3). The maximum winter ice extent occurred during late-April near the Pribilof Islands, or 920 km south of Bering Strait. Ice break-up began in late May and by mid-June most of the SLIP region was ice-free.

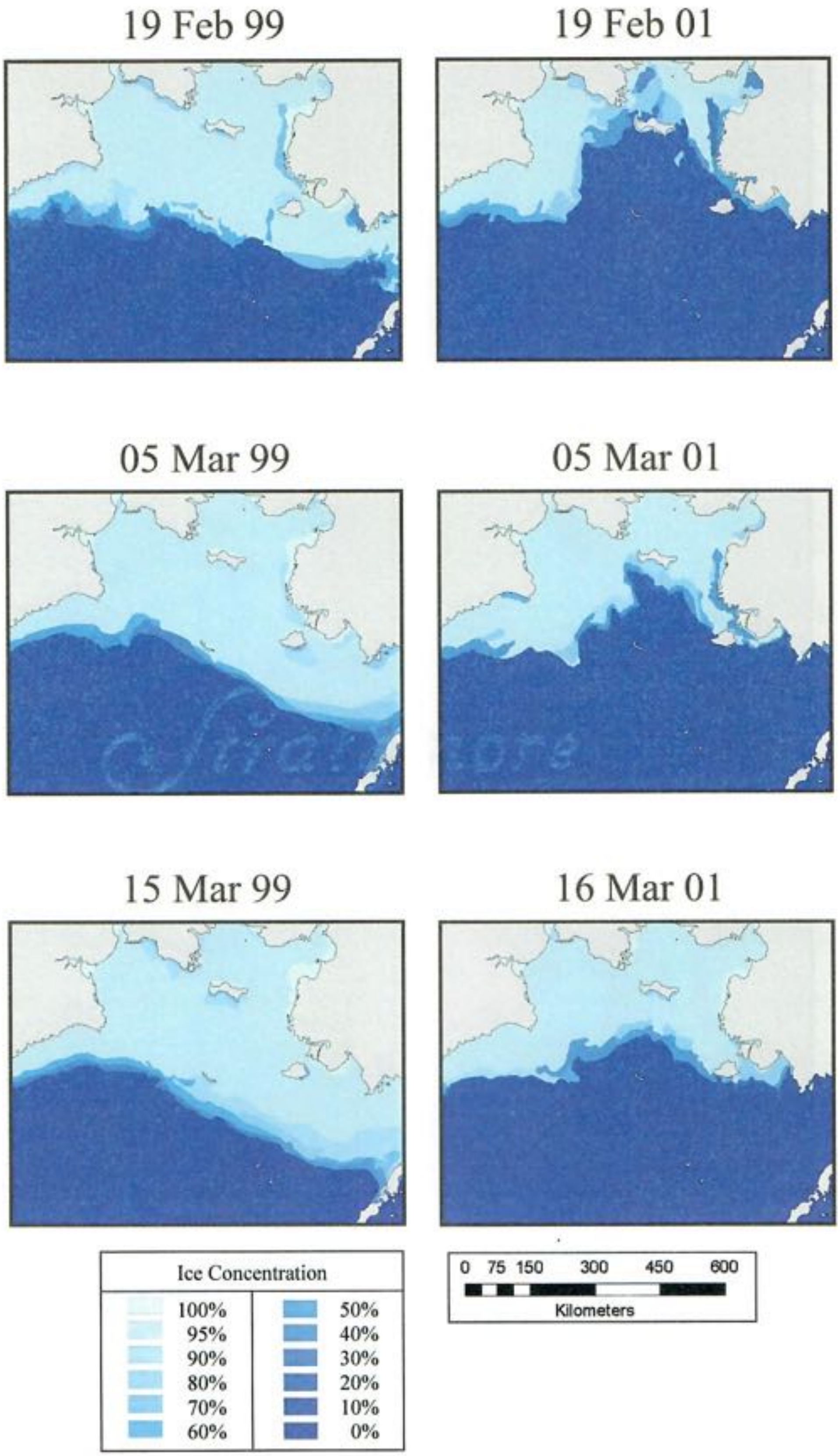


Figure 2. Bering Sea ice concentration during ice formation.

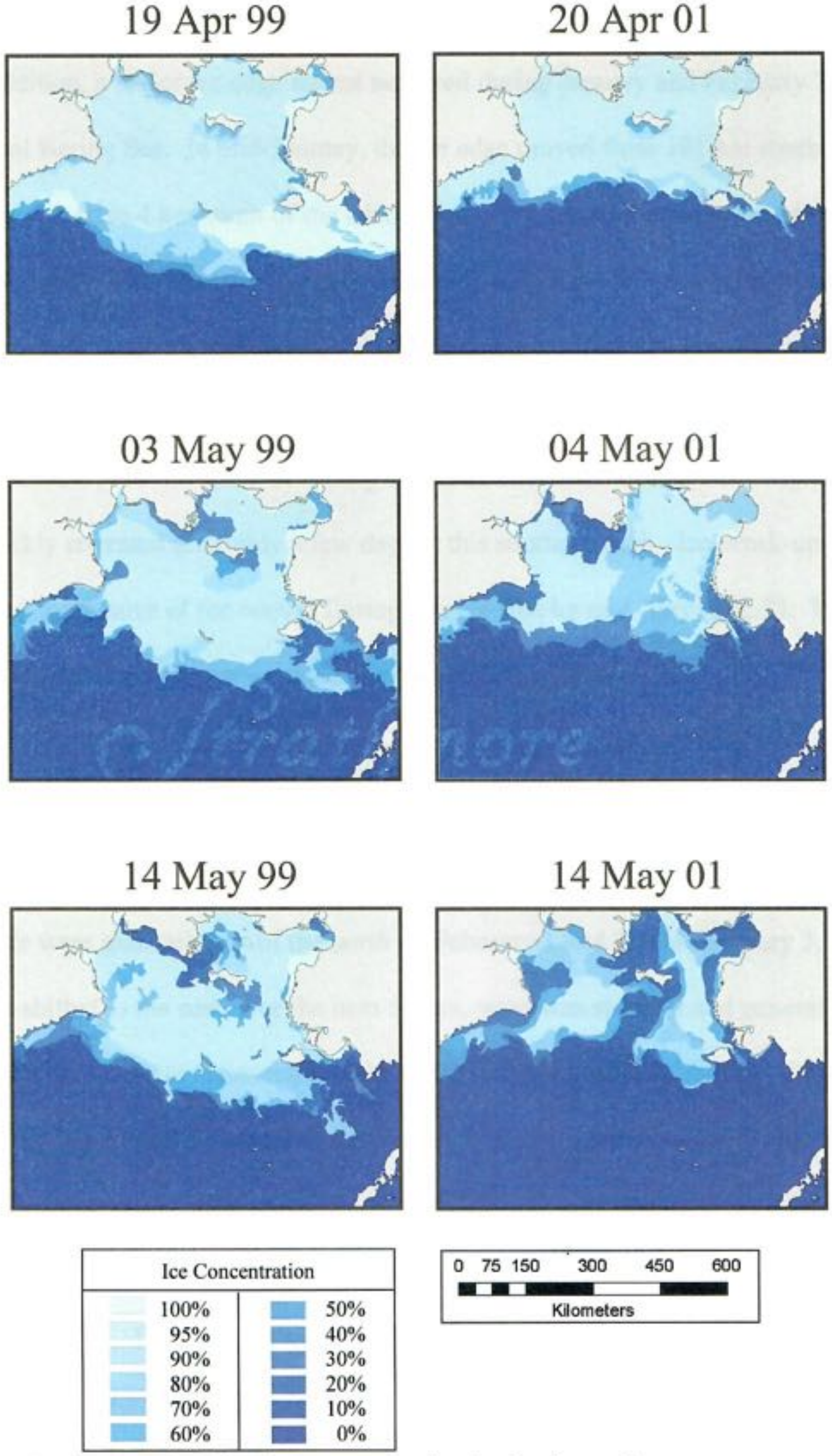


Figure 3. Bering Sea ice concentration during ice-melt.

Ice formed much more slowly in the Bering Sea during winter of 2000-01 (Fig. 2). In addition, a major ice edge retreat occurred during January and February 2001 for the central Bering Sea. In mid-January, the ice edge moved from 181 km south of St. Lawrence Island to 4 km south of the island with a low concentration north of the island to Bering Strait. This retreat was likely caused by a shift in wind direction. A southward ice edge progression resumed during early-March and reached 200 km south of St. Lawrence Island during mid-March (Fig. 2). Maximum extent reached just south of St. Matthew Island (730 km south of Bering Strait) and occurred during early-April. The ice edge quickly retreated after only a few days at this southern limit. Ice break-up began in early-May, with most of the central Bering Sea ice-free by mid May (Fig. 3). The western and eastern portions were ice-free by the first of June.

2. Wind

Wind data were collected at two different sites for analysis of wind speed and wind direction during February 2001. Data measured by a buoy at 57°N, 177°W shows that winds were generally out of the north on February 1 and 2. On February 3, the wind direction shifted to the east. For the next 5 days, wind was stronger and generally from the south (Fig. 4). Data measured at Nome, AK shows a generally eastern wind direction for the first five days of February. From February 6 to 14, wind is largely out of the south with some strong wind speeds up to 25 knots. Around February 15, wind direction becomes more variable, but is primarily out of the west and north until the end of February (Fig. 5). This wind forcing likely led to the reduced ice conditions in SLIP during February 2001 (Fig. 2).

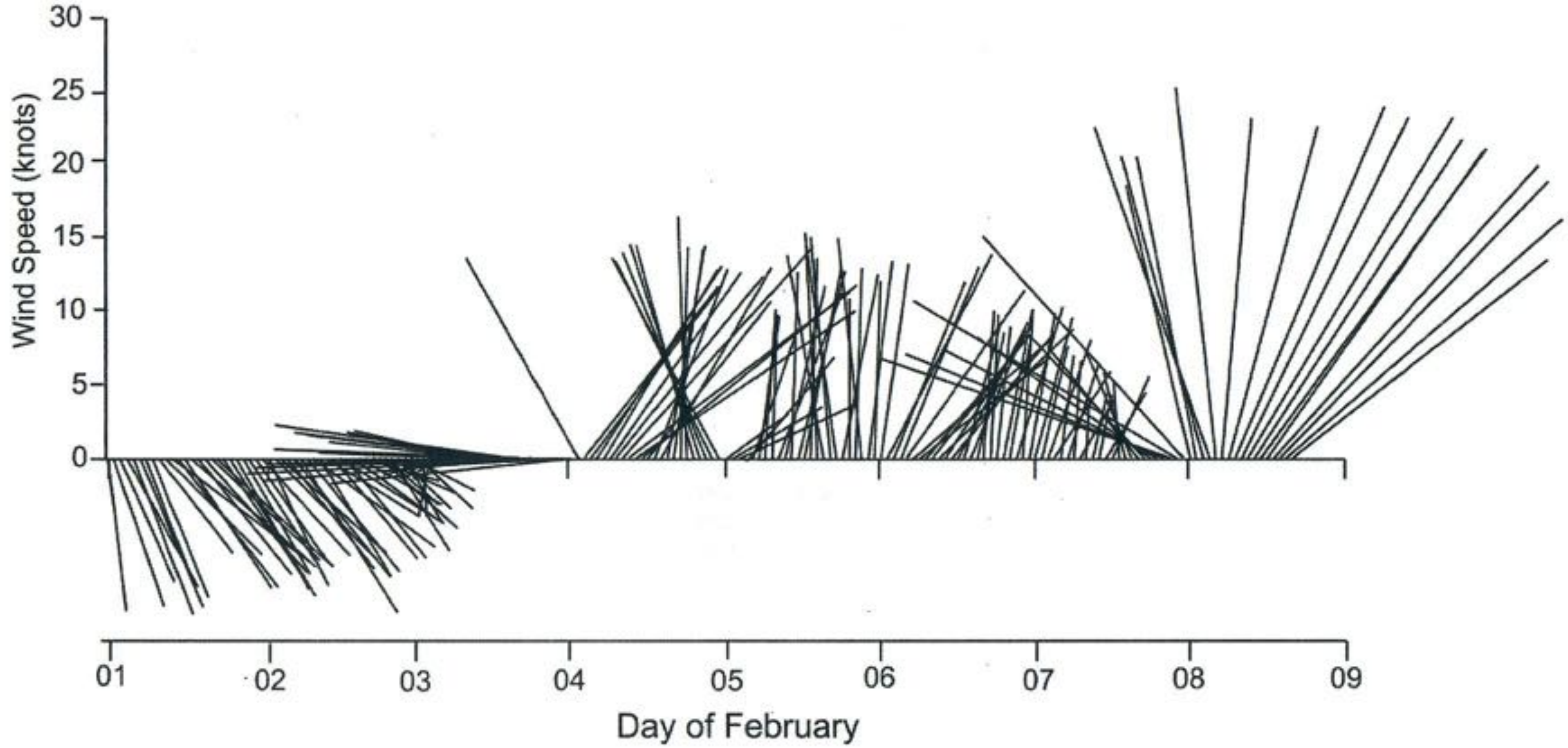


Figure 4. Hourly wind direction during February 2001 as measured at 57.08°N, 177.78°W by a NOAA data collection buoy. Data was obtained from the National Data Buoy Center website (www.ndbc.noaa.gov). Wind direction is presented as the direction the wind is coming from in degrees clockwise from North (e.g. North =0,360; East=90; South=180; West=270).

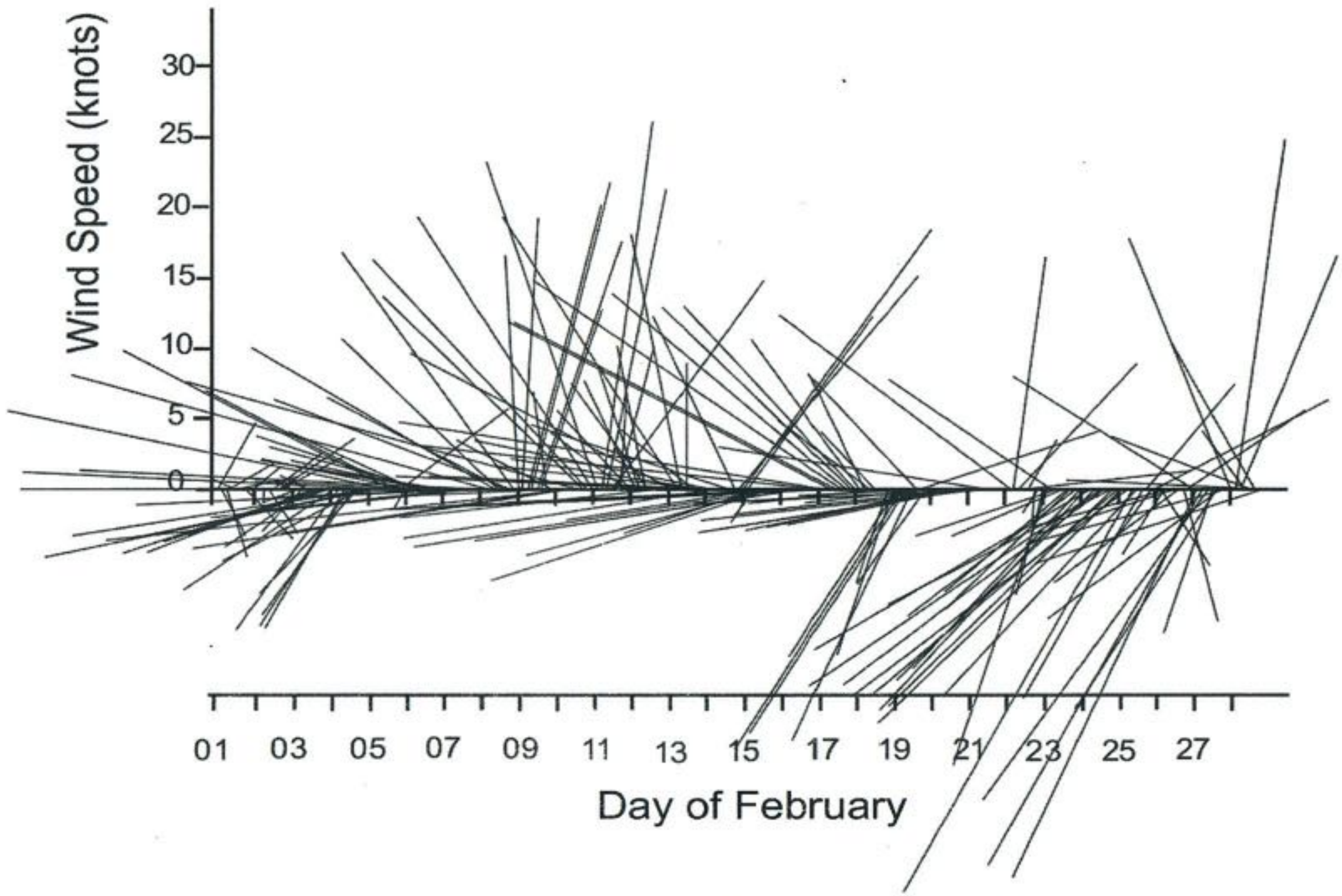


Figure 5. Wind direction during February 2001 as measured at Nome, AK (64.50°N, 165.28°W). Data was obtained from the U.S. National Weather Service (www.nws.noaa.gov). Wind direction and speed are 3-hour averages. Wind direction is presented as the direction the wind is coming from in degrees clockwise from North (e.g. North =0,360; East=90; South=180; West=270).

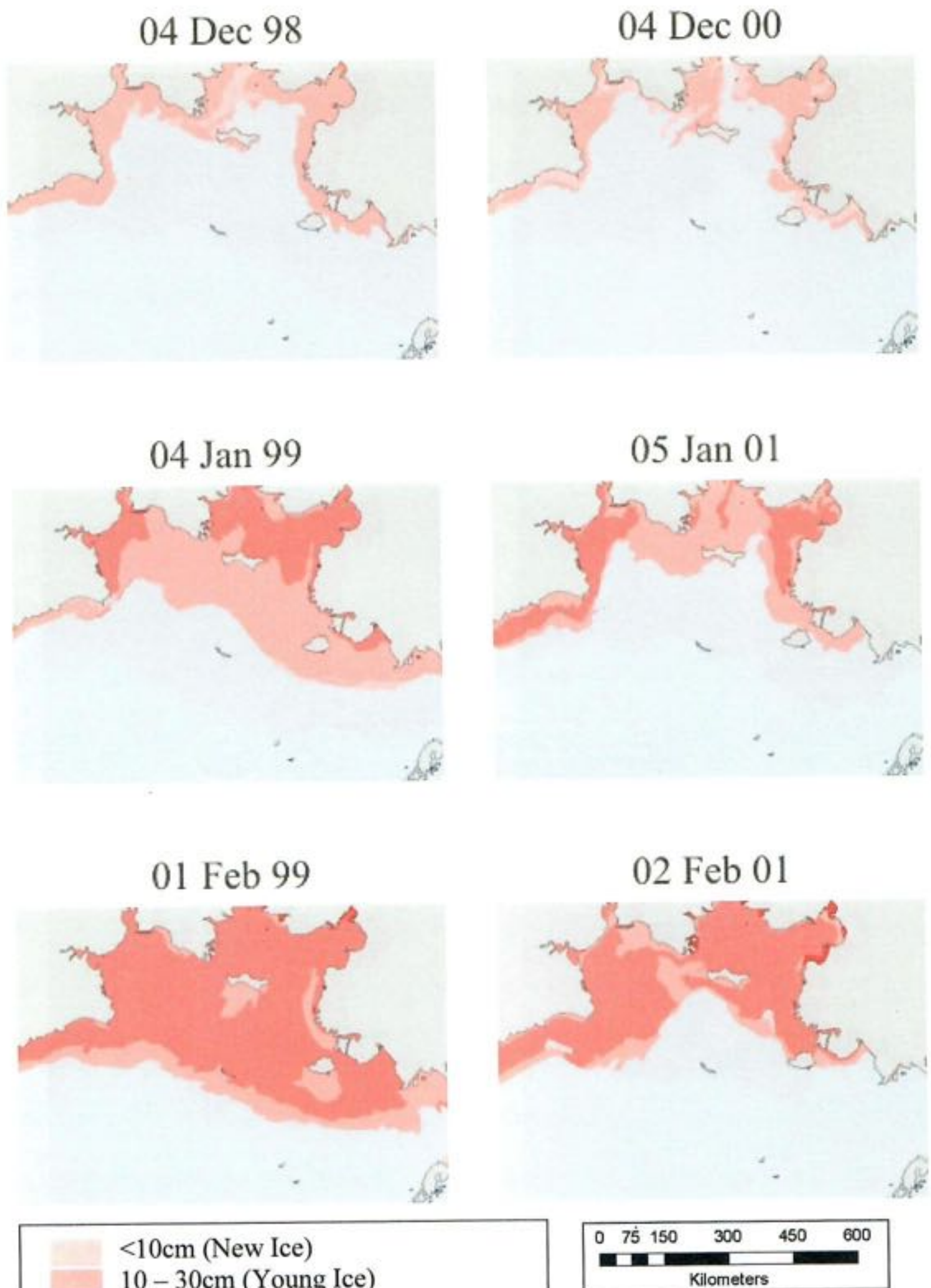
3. Ice thickness

In 1999, the SLIP region was predominately covered in young ice (10-30cm) from December through February (Fig. 6). In March the ice was mainly thin first year ice (30-70cm) becoming medium first year ice (70-120cm) in April, except for a polynya south of St. Lawrence Island, which was characterized by ice less than 10 cm thick (Fig. 7).

In 2001, SLIP was predominately covered by young ice (10-30cm) for the entire ice season (Figs. 6, 7). The only exception was during April, when the predominant stage of ice was thin, first-year ice (30-70cm) in the west (Fig. 7). It is noteworthy that unlike freshwater ice, sea ice is not stable, smooth, or uniform in thickness or concentration. Instead, it may be described as an incomplete cover, which is highly variable in form and structure (Fay 1974, Comiso 1995). These measures of ice thickness, therefore, should not be interpreted as absolute, but as estimates of the predominant stage of ice development.

4. Polynyas south of St. Lawrence Island

A polynya formed south of St. Lawrence Island in mid-January 1999. It extended 25 km south from the southern shore of the island. Except for a brief disappearance in early-March, the polynya was relatively constant over the winter and grew in size in early-April just prior to the beginning of ice-melt. The polynya in 2001 formed in mid-January as well. However, during February most of the central Bering was ice-free due to ice edge retreat up to the shore of St. Lawrence Island (SLI). By mid-March a polynya formed again south of the island and extended about 20 km south. While maps of ice concentration show the polynya to only extend 20-25 km south of SLI, maps of ice



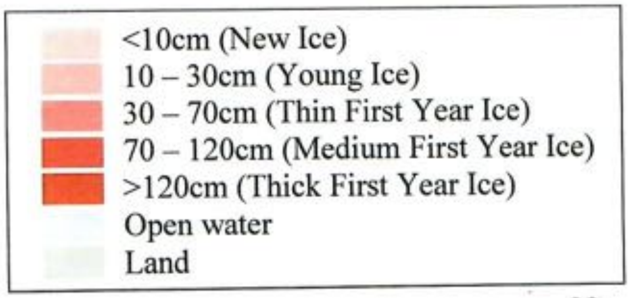


Figure 6. Winter ice thickness comparison between 1999 and 2001.

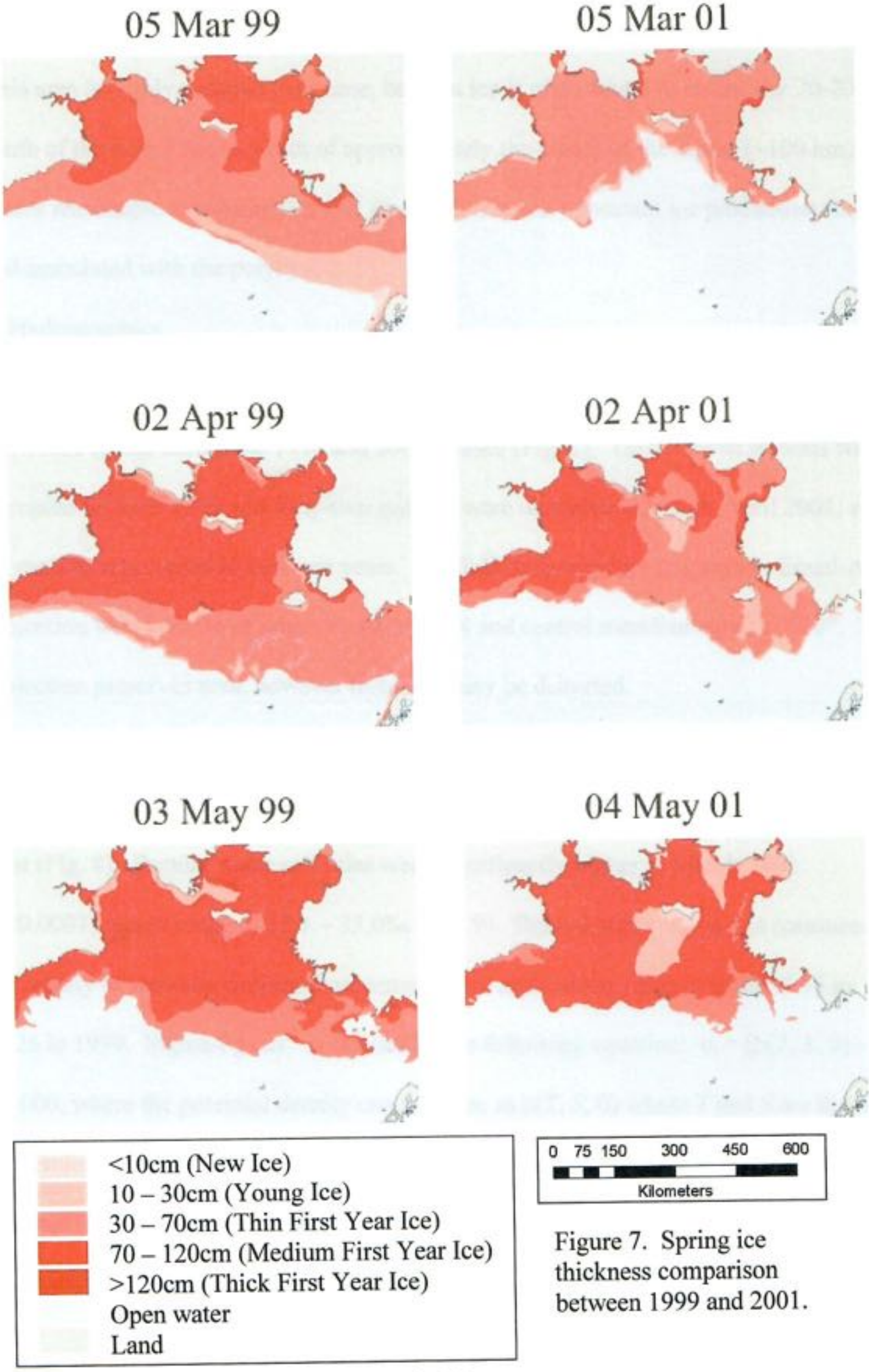


Figure 7. Spring ice thickness comparison between 1999 and 2001.

thickness give additional information by revealing a larger area of thin ice (Figs. 6, 7). This area is highly variable over time, but thin ice is often found to extend for 20-200 km south of the island with a width of approximately the length of the island (~100 km). It seems reasonable to assume that this area of thin ice an important ice production zone and associated with the polynya.

5. Hydrographics

Seventy-nine stations were occupied in the northern Bering Sea, south of St. Lawrence Island during the 1999 and 2001 cruises (Fig. 1). Thirty-seven stations were occupied in April 1999 and forty-two stations were occupied in March April 2001, with 30 stations reoccupied in between years. All field data maps are in Lambert Equal-Area projection with latitude of origin equal to 60°N and central meridian equal to 180°. This projection preserves area, however distances may be distorted.

Depths ranged from 43 to 80 m in 1999 and from 39 to 82 m in 2001. In 1999, bottom water salinities ranged from 31.6‰ in the east to 33.1‰ in nearshore areas in the west (Fig. 8). Bottom water salinities were significantly higher in March 2001 ($p<0.0001$) with a range of 32.1 – 33.0‰ (Fig. 9). Bottom water sigma-t (a measure of the density of seawater derived from temperature and salinity) ranged from 25.46 to 26.26 in 1999. Sigma-t g cm^{-3} is defined by the following equation: $\sigma_t = [\rho(T, S, 0) - 1] \times 1000$, where the potential density can be taken as $\rho(T, S, 0)$ where T and S are the *in situ* temperature and salinity and the zero denotes the condition of atmospheric pressure (Pickard 1975). The effect of pressure is ignored in this measurement because pressure has a very small effect on density at relatively shallow depths (Pickard 1975). Similar to

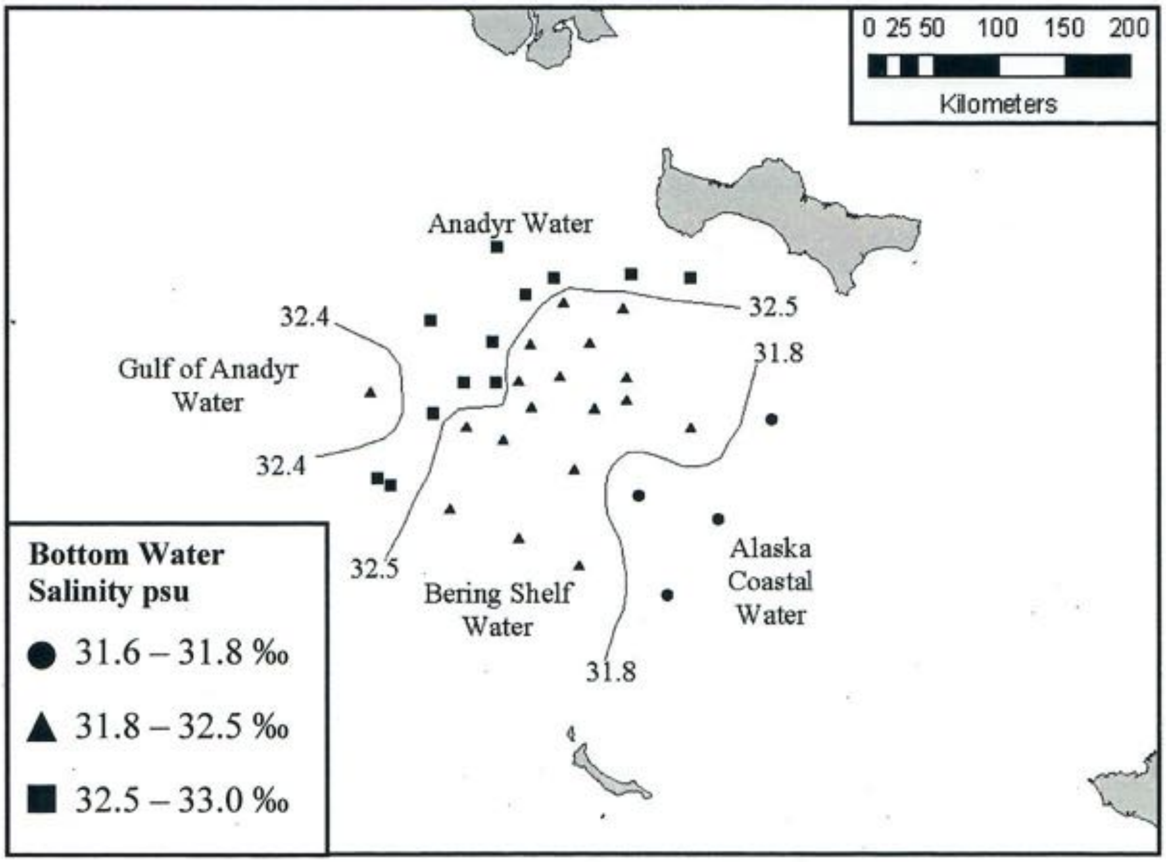


Figure 8. Bottom water salinity in April 1999.

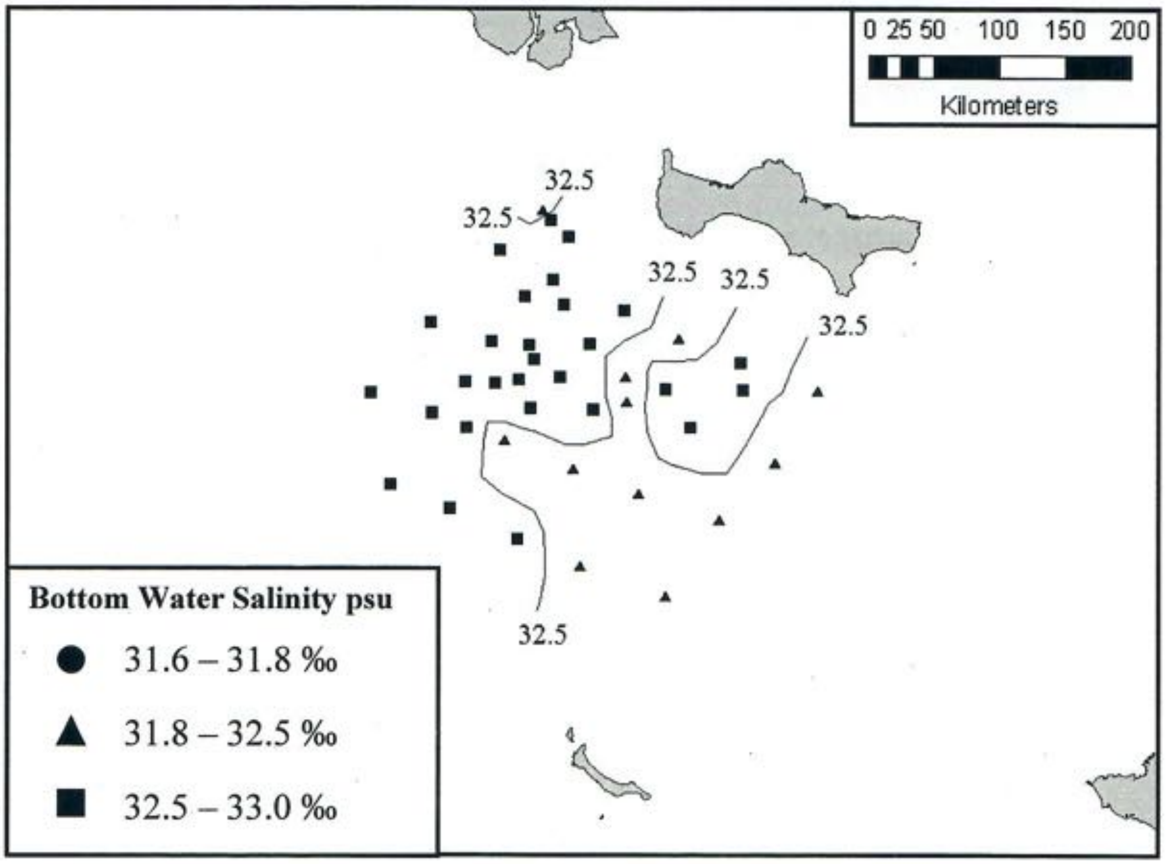


Figure 9. Bottom water salinity in March-April 2001.

bottom salinity, the lowest sigma-t values were found in the east and the highest in the west and nearshore. In 2001, sigma-t ranged from 25.81 to 26.50 g cm^{-3}, with lower values found in the central and eastern stations and higher values in the west. The Wilcoxon Signed Rank Test indicated a significant difference in bottom water salinity ($p<0.0001$) and bottom water sigma-t ($p<0.0001$) between years (Table 2). The difference in salinity seems to be rather constant over the entire study region as illustrated in Figure 10. The greatest differences in salinity between years are in the central and eastern part of SLIP, namely stations such as POP4, SEC3, SEC4, NEC3, NEC4, and NEC5 (Fig. 11). No other environmental parameters were significantly different from one another at an alpha of 0.05.

Water temperatures were cold in both years and the water column was almost completely isothermal at most stations. In 1999, the range of bottom water temperature was –1.80 to –1.67°C. A larger range (–1.80 to –1.19°C) occurred in March 2001 due to higher temperatures in six southerly stations (Figs. 12, 13). While there was no significant difference between years, it is important to note the warm bottom water at the six stations in 2001. Most stations in SLIP were covered by ice at least by the first of March, however these six stations were not covered until the end of March.

6. Biological measurements and tracers

In 1999, bottom water chl-*a* ranged from <0.01 mg m^{-3} in the southeast to 1.16 mg m^{-3} nearshore SLI. Values ranged from 0.04 mg m^{-3} in the west to 0.85 mg m^{-3} in the center of SLIP in 2001. Integrated water column chl-*a* ranged from 9.43 mg m^{-3} to 78.20 mg m^{-3} in 1999 and from 3.11 mg m^{-3} to 54.22 mg m^{-3} in 2001 (Fig. 14). Sediment chl-*a* ranged from 4.15 to 13.41 mg m^{-2} in 1999 and 0.12 to 17.05 mg m^{-2}.

Table 2. Wilcoxon signed rank test results for differences in various parameters measured at 30 reoccupied stations in 1999 and 2001.

Parameter	p-value
Surface water temperature	0.1338
Bottom water temperature	0.4528
Bottom water salinity	**<0.0001**
Bottom water sigma-t	**<0.0001**
Bottom water chl-*a*	0.0672
Integrated water column chl-*a*	0.1359
Sediment chl-*a*	0.9425

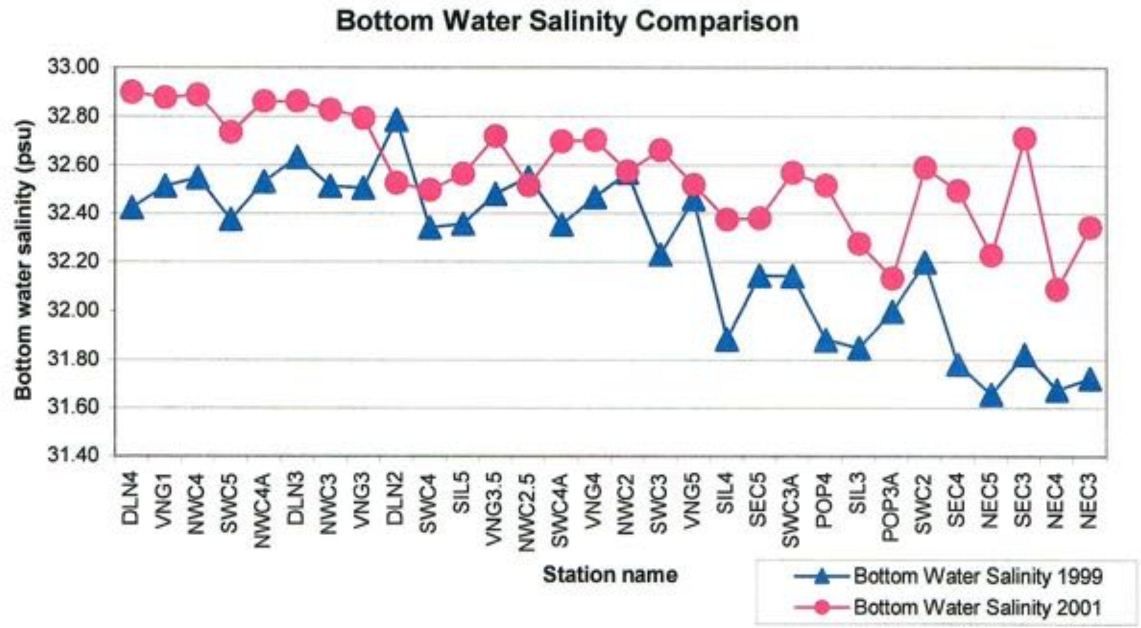


Figure 10. Bottom water salinity comparison between 1999 and 2001. Stations are arranged by longitude with western stations on the left and eastern stations on the right. Station locations are indicated in the following figure.

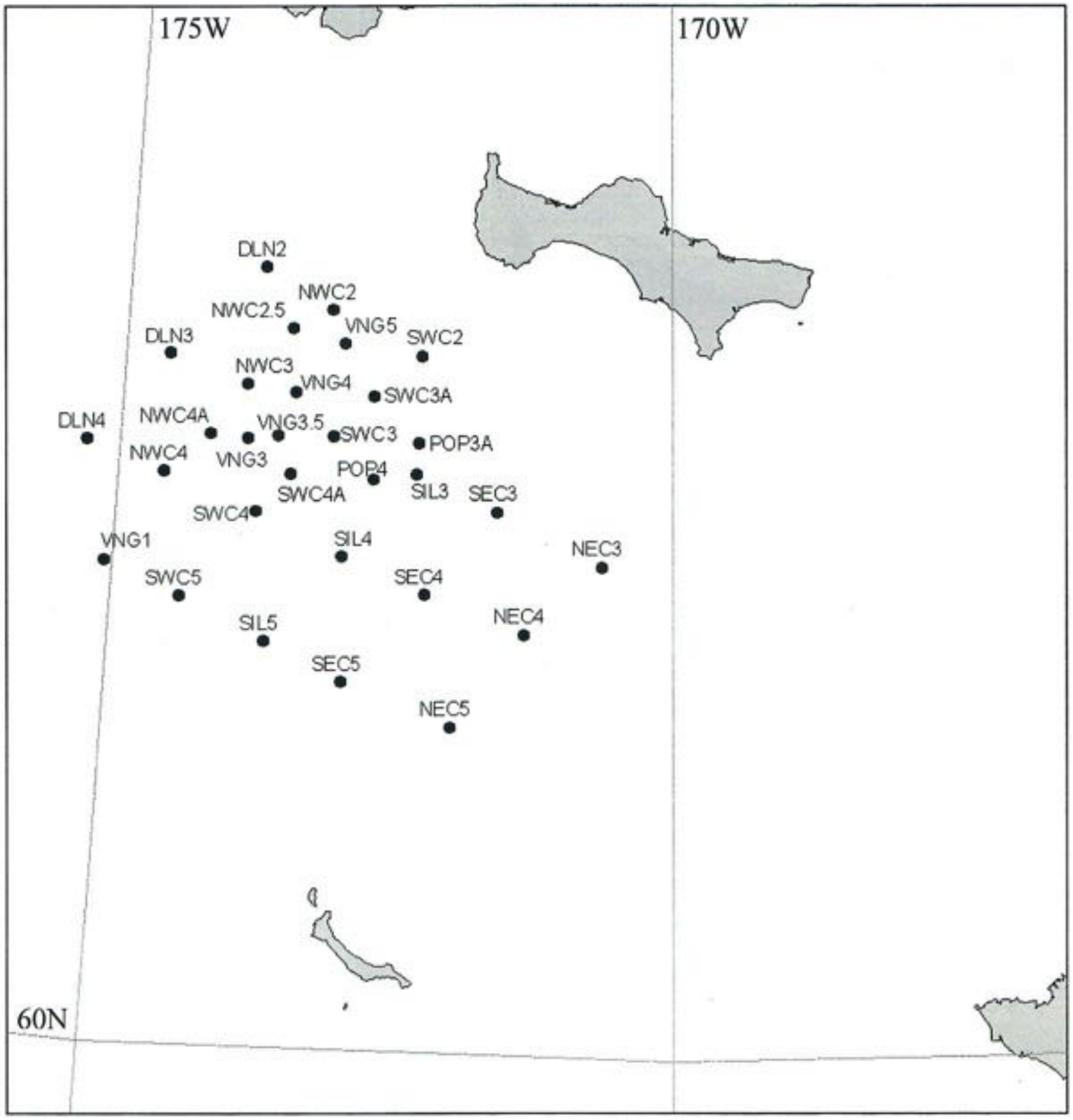


Figure 11. Station locations and station names during SLIPP99 and SLIPP01.

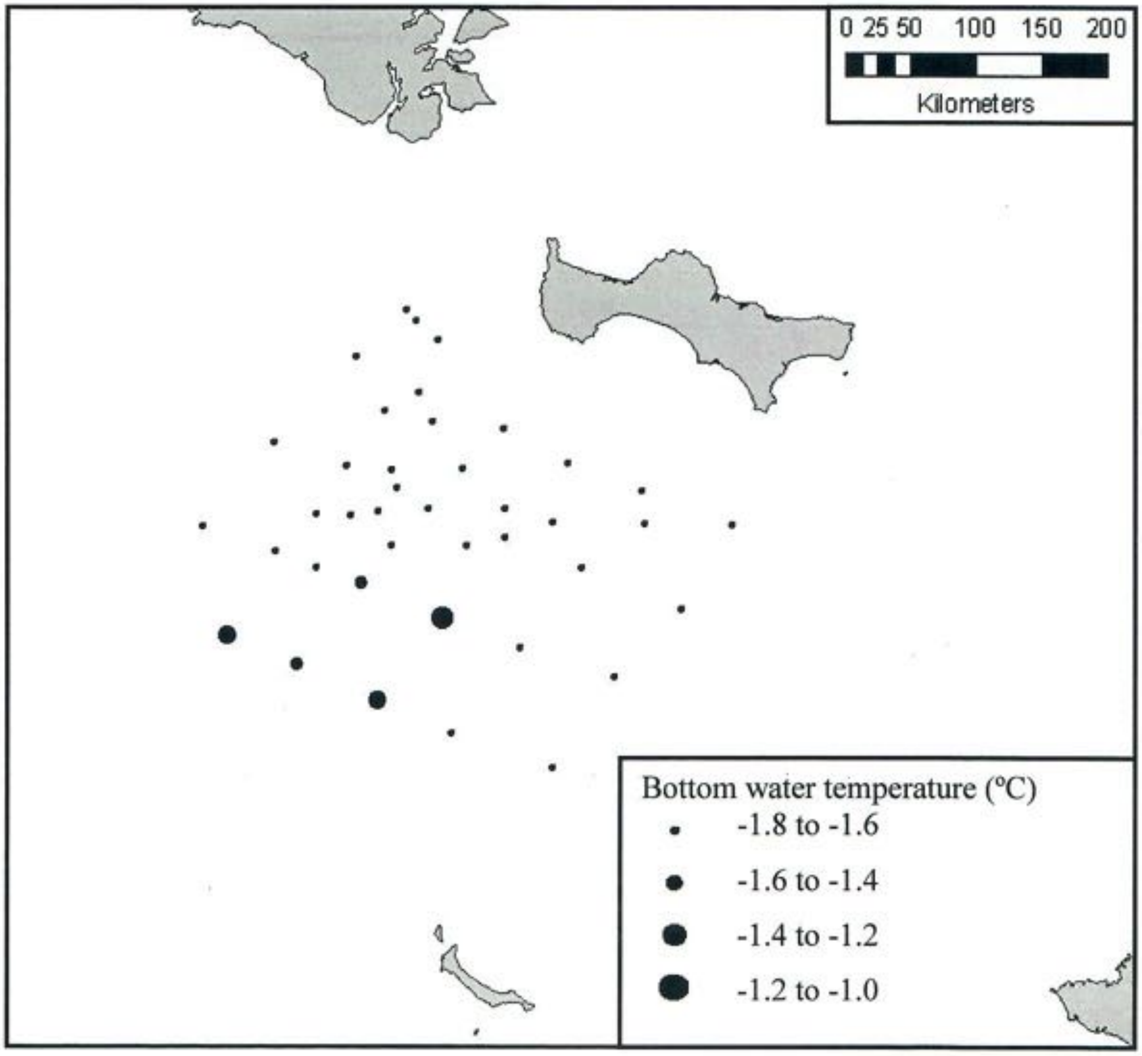


Figure 12. Bottom water temperature in March-April 2001.

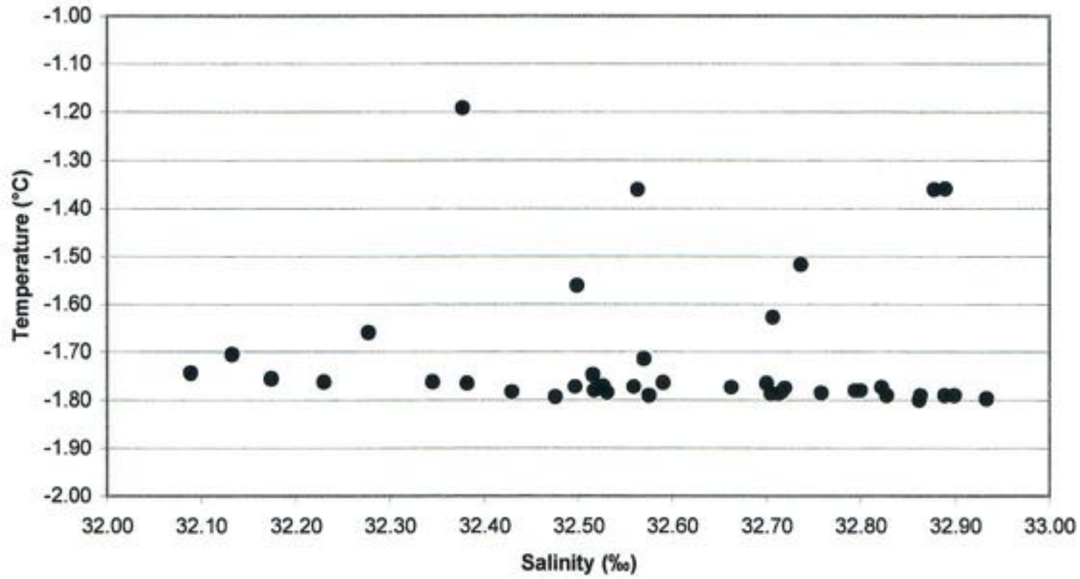


Figure 13. SLIPP01 T/S plot.

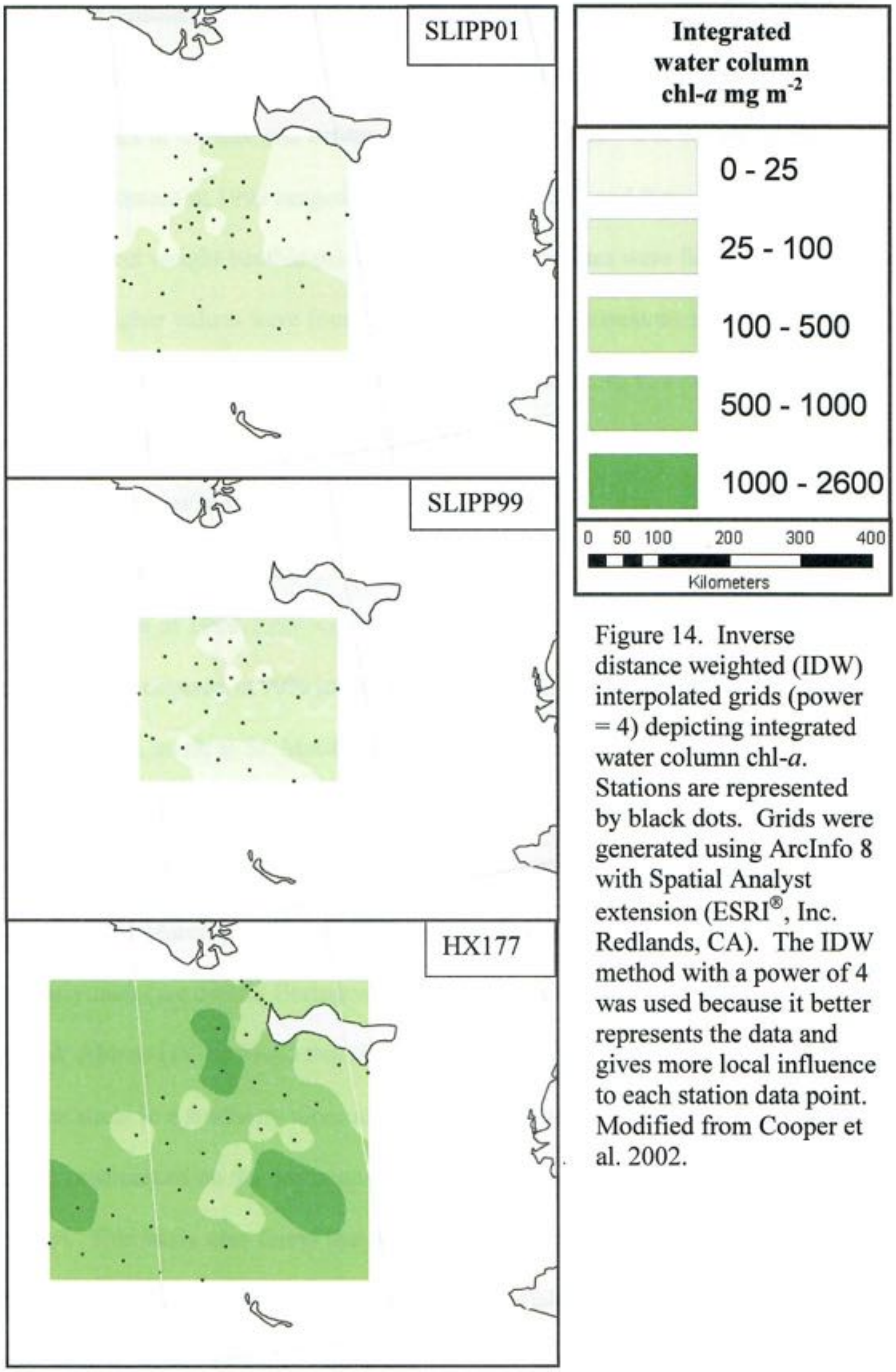


Figure 14. Inverse distance weighted (IDW) interpolated grids (power = 4) depicting integrated water column chl-*a*. Stations are represented by black dots. Grids were generated using ArcInfo 8 with Spatial Analyst extension (ESRI®, Inc. Redlands, CA). The IDW method with a power of 4 was used because it better represents the data and gives more local influence to each station data point. Modified from Cooper et al. 2002.

Abundance of benthic organisms was 968 to 5,993 individuals m^{-2} in 1999 and 993 to 10,005 individuals m^{-2} in 2001. Lower abundances were found in the west and southwest and higher values in the east and center of SLIP in both years. Wet weight benthic macrofaunal biomass in 1999 ranged from 57 to 1326 g m^{-2} and from 54 to 1373 g m^{-2} in 2001. Lower wet weight benthic macrofaunal biomass values were found in the east and center, while higher values were found in the west and southwest during both years. Organic carbon benthic macrofaunal biomass ranged from 2.45 to 42.53 g C m^{-2} in 1999 and from 2.41 to 42.64 g C m^{-2} in 2001 (Fig. 15). Lower values were again found in the east and higher values in the west.

D. Discussion and conclusions

The winter of 1998-1999 was characterized by early ice formation (most of the study region was covered in 90% ice by early-December 1999), extensive coverage (the entire Bering Sea, south to St. Matthew Island was covered in 90% ice from January to April, except for the polynya south of St. Lawrence Island), and typical melt timing (Figs. 2, 3). By contrast, the winter of 2000-2001 was characterized by late ice formation (SLIP not covered until March), thin ice (the predominant stage of development was young ice), and an early melt (the central Bering was ice-free by mid-May) (Figs. 2, 3, 6, 7). Muench & Ahlnäs (1976) found that the region south of St. Lawrence Island had the highest ice shear in a southerly direction in the Bering Sea from March to June 1974. They also commented on the common presence of new ice and lower ice concentration in this region. This study also found that ice concentration was generally lower from the coastline of St. Lawrence Island to about 20-25 km offshore from January through April in both years. In 2001, a much larger area of reduced ice thickness was apparent

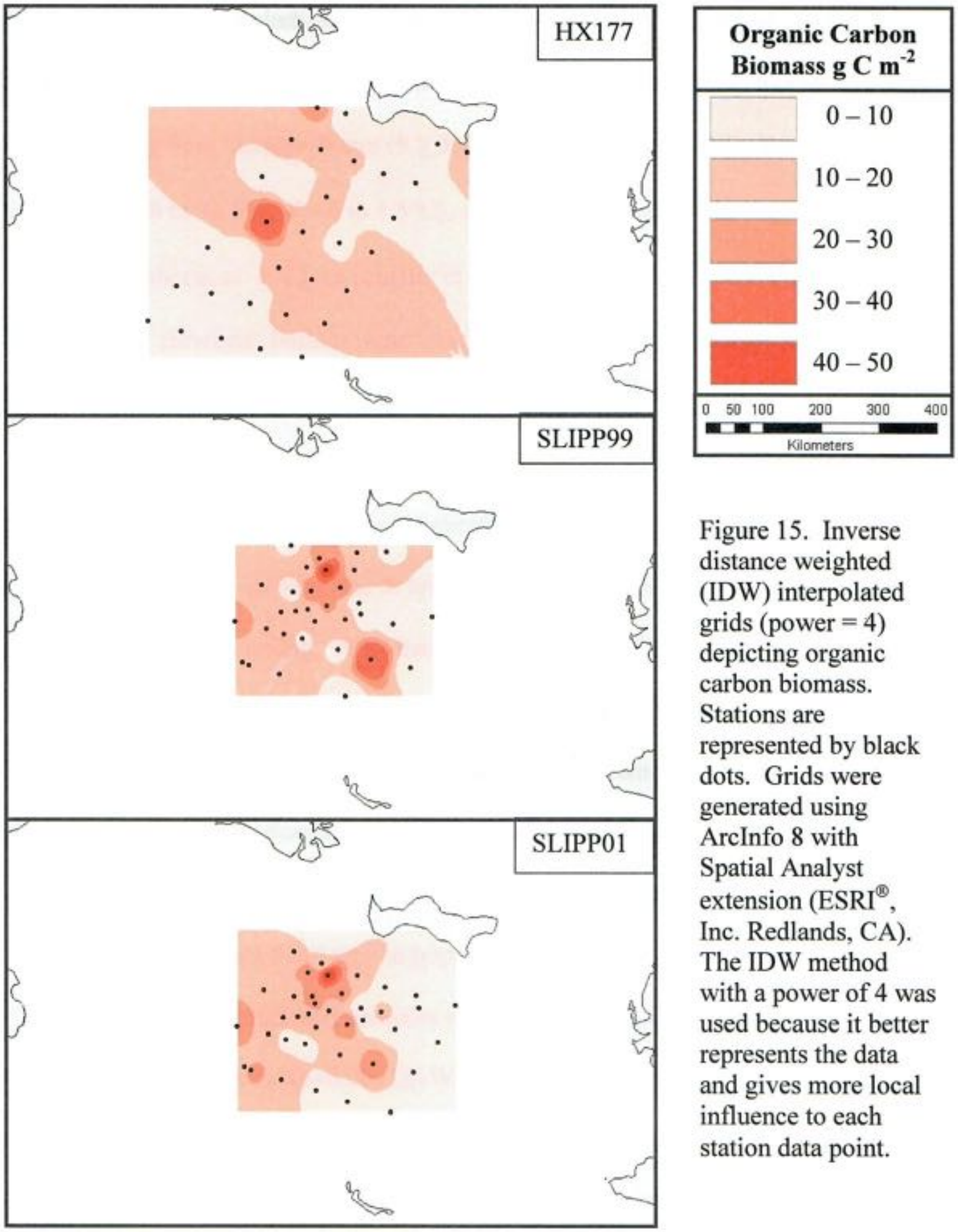


Figure 15. Inverse distance weighted (IDW) interpolated grids (power = 4) depicting organic carbon biomass. Stations are represented by black dots. Grids were generated using ArcInfo 8 with Spatial Analyst extension (ESRI®, Inc. Redlands, CA). The IDW method with a power of 4 was used because it better represents the data and gives more local influence to each station data point.

throughout the year, also indicative of polynya action (Figs. 6, 7). Bottom water temperature and salinity profiles can be used to define 3 summer water masses in the northern Bering Sea: Anadyr Water (S $\geq$ 32.5‰, T = -1.0°C to 1.5°C), Bering Shelf Water (S = 31.8 to 32.5‰, T = 0 to 1.5°C), and Alaska Coastal Water (S $\leq$ 31.8‰, T = $\geq$ 4°C) (Schumacher et al. 1983, Grebmeier et al. 1988, Walsh et al. 1989, Grebmeier & Cooper 1995). However, bottom water temperatures in winter are colder for each water mass.

Paired comparison tests between data collected during March 2001 and April 1999 revealed significant differences in salinity and sigma-t. The high salinity and sigma-t in March 2001 is likely due to brine injection within the St. Lawrence Island polynya just prior to sampling. After the wind direction shift in early-February, this polynya formed and ice formation resumed in late-February. As this new ice was produced, brine was likely rejected and high saline water sank to the seafloor, raising salinity and increasing bottom water density. SLIP was covered in young ice (10-30 cm) during early-April, while surrounding areas were characterized by thicker sea ice (Fig. 7). Therefore, it is likely that SLIP was an important ice production zone at this time.

In contrast, salinities and densities in April 1999 were significantly lower than those made in March 2001 ($p<0.0001$). While bottom water temperature was almost constant across the region in April 1999 (–1.80 to –1.67°C), salinity values were similar in range and distribution to summertime values measured by Grebmeier & Cooper (1995). These "normal salinities" in April 1999 show at least a temporary, if not permanent, end to large-scale ice production and an influx of new water advected onto the shelf.

Ice data seems to indicate much earlier polynya action in 1999 as compared to 2001. Ice thickness maps show a polynya in early-February 1999, while the polynya did not form until March during 2001, due to a relatively late ice edge progression (Fig. 2). These temporal differences may be why high salinities were detected in 2001 and not in 1999. Pease (1980) found little *in situ* ice formation south of 62°N latitude, indicating that most ice forms in the northern Bering Sea and is pushed south by winds. This work also predicted that northern ice production zones would show an increase in salinity from 1.25-7.5‰ over the winter season. My data show a smaller, but significant difference in salinity of 0.34‰ between April 1999 and March-April 2001.

Statistically there was no significant difference in bottom water temperature between years for all 30 stations combined. However, an area in the southern part of SLIP was noticeably divergent. In 2001, the bottom water was 0.2 - 0.5°C warmer than in 1999 at six southern stations (Fig. 12). This region was also the last part of SLIP to be covered by ice in 2001.

In spite of the extreme differences in ice coverage, measurements of chl-*a*, both in water and sediment, were not significantly different between 1999 and 2001. This finding can be attributed to low light levels during late-winter/early-spring and a mixed water column. Upon finding similar results in the southeast Bering in winter during the late 1960's and early 1970's, McRoy & Goering (1974) attributed low chl-*a* values to low light intensities caused by the winter sun, ice cover, and strong vertical mixing. It is likely that the same wind events which impeded ice edge migration during February 2001 caused the water column to be vertically mixed.

The distribution of benthic biomass follows the path of overlying water masses. The high-nutrient Anadyr Water in the western part of SLIP promotes high water column production and, therefore, supports a high benthic standing stock (Grebmeier & Cooper 1995). The low-nutrient, less productive Alaska Coastal Water restricts the growth of the benthos in the eastern portion of the region (Grebmeier et al. 1988, Grebmeier et al. 1995). Benthic biomass did not change significantly over the 2-year period for all 30 stations combined. This is not surprising in light of the fact that benthic invertebrates in this area are slow growing, long-lived animals (Clarke 1980, Feder & Jewett 1981). Benthic macroinvertebrates in the Bering Sea have been viewed as long-term integrators of overlying water column processes, both physical and biological (Grebmeier et al. 1988, Grebmeier & Dunton 2000). Changes in the dynamics of biological communities will be helpful in determining large-scale, low-frequency changes in climate and physical processes (Hare & Mantua 2000, Hare et al. 2000).

III. Sea ice influence on water column and benthic processes: The transition from winter to spring

A. Introduction

Sea ice is an important feature of the Arctic ecosystem for a number of reasons. Examples include providing a habitat for sea ice organisms (Alexander & Chapman 1981), acting as a platform for marine mammals (Fay 1974), and creating a stratified water column during ice-melt (Alexander 1981). In the Arctic and surrounding seas, ice algae live on the underside of ice near the ice-water interface (Alexander & Chapman 1981). Work in the Antarctic has revealed algal communities present in and on the surface of ice flows as well as in the bottom ice layer (Cota & Sullivan 1990, Legendre et al. 1992, Arrigo et al. 1998). These algal communities, commonly dominated by pennate diatoms, appear in late-winter and increase until ice-melt (approximately 2 months), at which time they are released into the water column (McRoy & Goering 1974, Cota & Horne 1989, Thomas et al. 1998). Solar radiation, strongly influenced by snow depth and ice thickness, and nutrient availability seem to be the most important factors influencing sea ice algal growth (Cota et al. 1987, Perovich et al. 1993). Over a 50-day period, Smith et al. (1988) estimated sea ice algal production to be 5 to 23 g C m^{-2}, in Resolute Passage in the Canadian Arctic. Cota and Sullivan (1990) estimated ice algal production in McMurdo Sound, Antarctica to be 6.6 to 13.2 g C m^{-2} over 41 days in spring.

The polar bear uses the ice as an extension of land upon which to hunt prey, mainly seals (Burns 1981). Protection from predation by killer whales may be a benefit to ice-inhabiting whale populations, although no direct benefit of ice on whales has been quantified (Burns 1981). Seals and walruses use the ice as a substrate upon which they feed, mate, bear young, and rest. Ice is also used as transportation to feeding grounds in the northern Bering Sea, which might be otherwise inaccessible due to long travel distances (Fay 1974).

Ice-edge regions have sharp horizontal gradients in salinity and, therefore, may be thought of as frontal zones (Alexander 1981). The difference between an ice-melt bloom and an open water bloom is the type of stratification. Ice-melt blooms are stratified by salinity gradients due to melt water and open water blooms are stratified by temperature gradients due to surface water heating (Niebauer et al. 1990, Niebauer et al. 1995). During ice-melt, a surface layer with low salinity, forms and stabilizes the water column (McRoy & Goering 1974, Alexander 1981, Niebauer et al. 1981). This stability is thought to be a key component, along with high nutrient availability and high light levels that triggers a spring ice-melt phytoplankton bloom (McRoy & Goering 1974, Alexander 1981, Niebauer et al. 1981). Stabeno et al. (1998) found that this stabilization and stratification allows phytoplankton growth to exceed respiration loss at the ice edge of the southeast Bering Sea. Niebauer et al. (1995) found a high degree of interannual variability in the intensity and timing of the Bering Sea ice edge bloom. This variability was linked with local weather patterns, requiring calm, sunny weather for bloom initiation. The length of time during which the bloom continues depends largely on the continual availability of nutrients. A highly stratified water column, influenced by salinity gradients, may prevent the influx of nutrients and truncate the phytoplankton bloom (Alexander 1981). Other work in the southeast Bering Sea during ice-melt shows that the ice-melt bloom sinks to the seafloor relatively ungrazed due to cold water temperatures and lack of zooplankton (Niebauer et al. 1990).

B. Methods

In this chapter, I utilize ice and field data from 1994, 1999, and 2001 and examine the transition from winter to spring. Specifically, this chapter contains sea ice concentration data from January through June 1994 and field data including 61 stations in May-June 1994. In addition, sea surface temperature and phytoplankton pigment concentration were evaluated during spring 1999 and 2001.

1. Retrieval of Bering Sea ice maps for 1994

Ice maps for the year of 1994 were obtained from a CD-ROM distributed by the National Snow and Ice Data Center entitled "Environmental Working Group Joint U.S. Russian Sea Ice Atlas for the Arctic Ocean." The maps were produced by the National Ice Center on the Wednesday of each week in ArcInfo (ESRI®, Inc. 2000) grid format with each grid cell representing 12.5 km. The projection of all ice maps was Polar Stereographic with the central meridian at 180° and the latitude of true scale at 60°N. Data was obtained for the period from the first week in January through the end of June. The maps were derived from a number of sources, meaning the accuracy of the spatial resolution is uneven.

2. Hydrographic, biological, and sediment data collection in 1994

Depth, bottom water salinity, bottom water sigma t, and bottom water temperature, were collected using a conductivity-temperature-depth profiler. Water column chl-*a*, sediment chl-*a*, and benthic biomass samples were collected and processed in the same manner as previously described (also see Cooper et al. 2002 for further description of methodology).

3. Sea Surface Temperature

Sea surface temperature (SST) data was collected from the Satellite Active Archive website administered by the National Oceanic and Atmospheric Administration (http://www.saa.noaa.gov). SST was measured by the Polar-Observing Environment Satellite (POES) using two types of sensors: Advanced Very High Resolution Radiometer (AVHRR) and High resolution Infrared Radiation Sounder (HIRS). Data from June 8, 1999 and June 9, 2001 were used in a comparison of SST after ice-melt. The region of interest was along 62°N from 170°W to 180° longitude with measurements made every 0.5° of latitude and longitude. The Wilcoxon Signed Rank test, a nonparametric, paired comparison test, was applied to SST data in order to test the hypothesis that there was a difference in SST between years. This nonparametric test was used because of a small sample size (n= 21).

4. Phytoplankton pigment concentration in May and June 1999 and 2001

Phytoplankton pigment concentration data was obtained from the Goddard Distributed Active Archive Center (DAAC). The DAAC maintains a website (http://daac.fsfc.nasa.gov/data/dataset/SEAWIFS/index.html) from which Sea-viewing Wide Field-of-view Sensor (SeaWIFS) data were accessed and downloaded as Graphical Interface files (.gif). Daily phytoplankton pigment concentration was examined for the Bering Sea throughout May and June 1999 and 2001. It is important to note that SeaWIFS data only provides the surface water pigment concentration with no regard to subsurface fluorescence.

5. Statistics

A correlation matrix was created for each cruise dataset using the statistical software package Statview 4.5© (Abacus Concepts 1995). The nonparametric correlation coefficient, Spearman's rho, and the p-value are reported for each correlation.

C. Results

Sea ice concentration was evaluated on a weekly basis from January through June 1994. Field data collection included 61 stations in May-June 1994. Sea surface temperature and phytoplankton pigment concentration were evaluated during spring 1999 and 2001.

1. Ice characteristics during 1994

Ice formation, extent, and melt-time can be considered average for the year 1994. By the first of January, SLIP was covered in 90% ice, which was present until the end of April. However, at certain times during April some areas in and near SLIP were characterized by lower concentrations (70-80%) indicating the onset of ice-breakup. While SLIP was showing signs of ice-melt in late April, the southern Bering Sea, near and along the shelf-break, was still under heavy ice. This scenario of ice-melt beginning in SLIP and a persistent, outer, southern ice rim is typical of ice descriptions for the 1970's (McNutt 1981). In early-May, an area in western SLIP broke open (~10% ice concentration) just prior to sampling (Fig. 16). As spring progressed, this area grew in size and by early June most of SLIP was ice-free (Figs. 17, 18, 19).

2. Hydrographic, biological, and sediment characteristics during spring 1994

Sixty-one stations were occupied in late-May/early-June 1994 over a larger sampling region than in 1999 and 2001 (Fig. 1). Depth ranged from 15-185 m, with

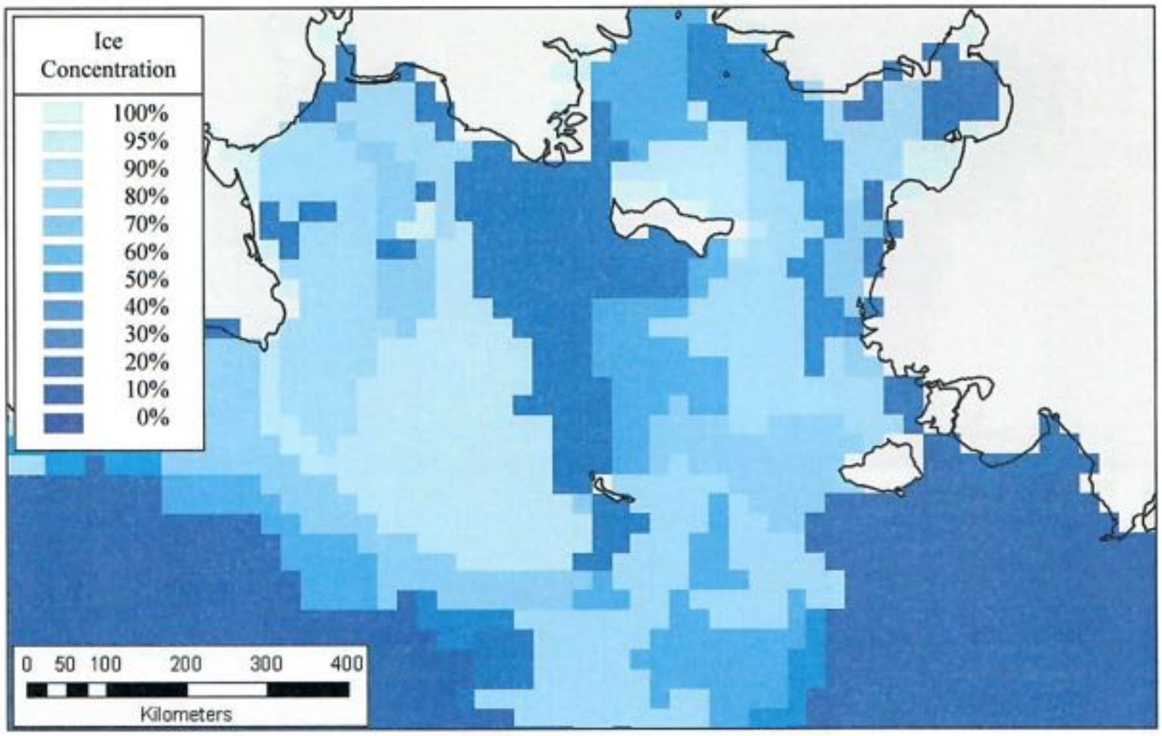


Figure 16. Ice concentration on May 11, 1994.

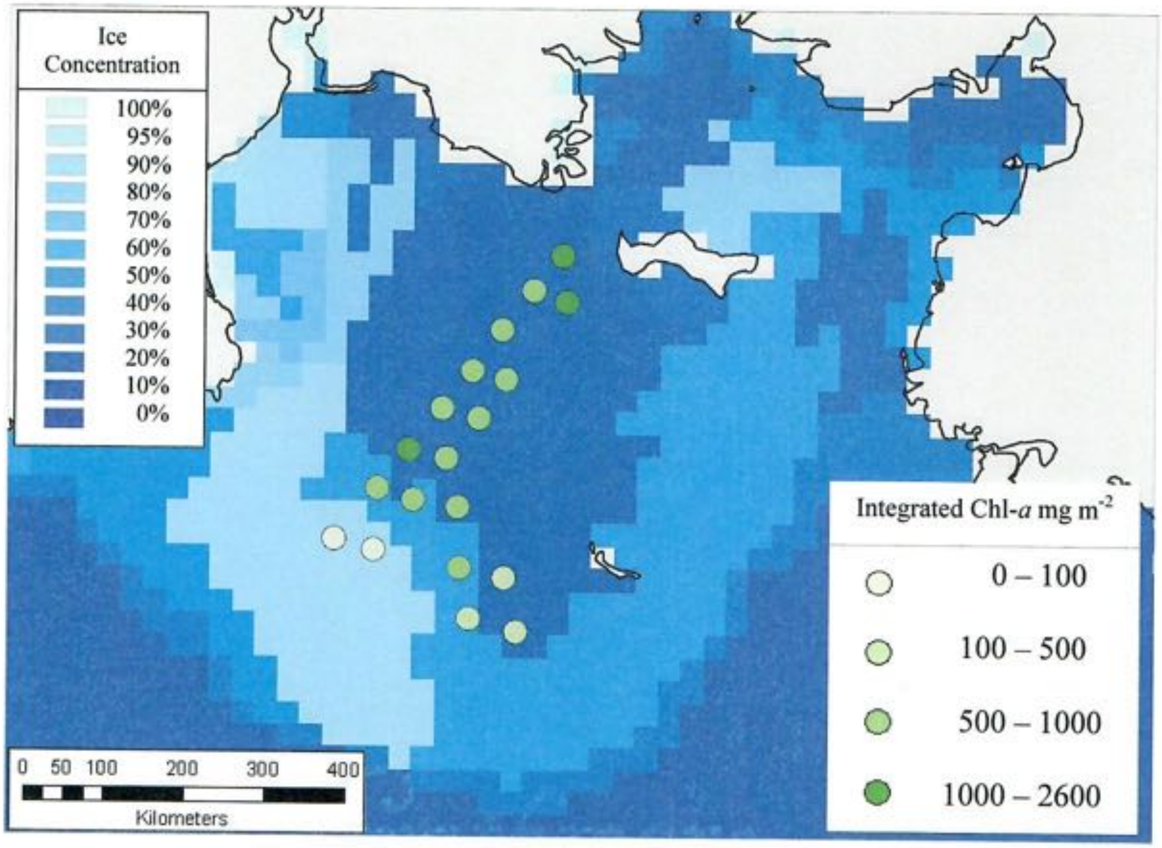


Figure 17. Ice concentration on May 25, 1994 and integrated chl-*a* for stations sampled May 22-28.

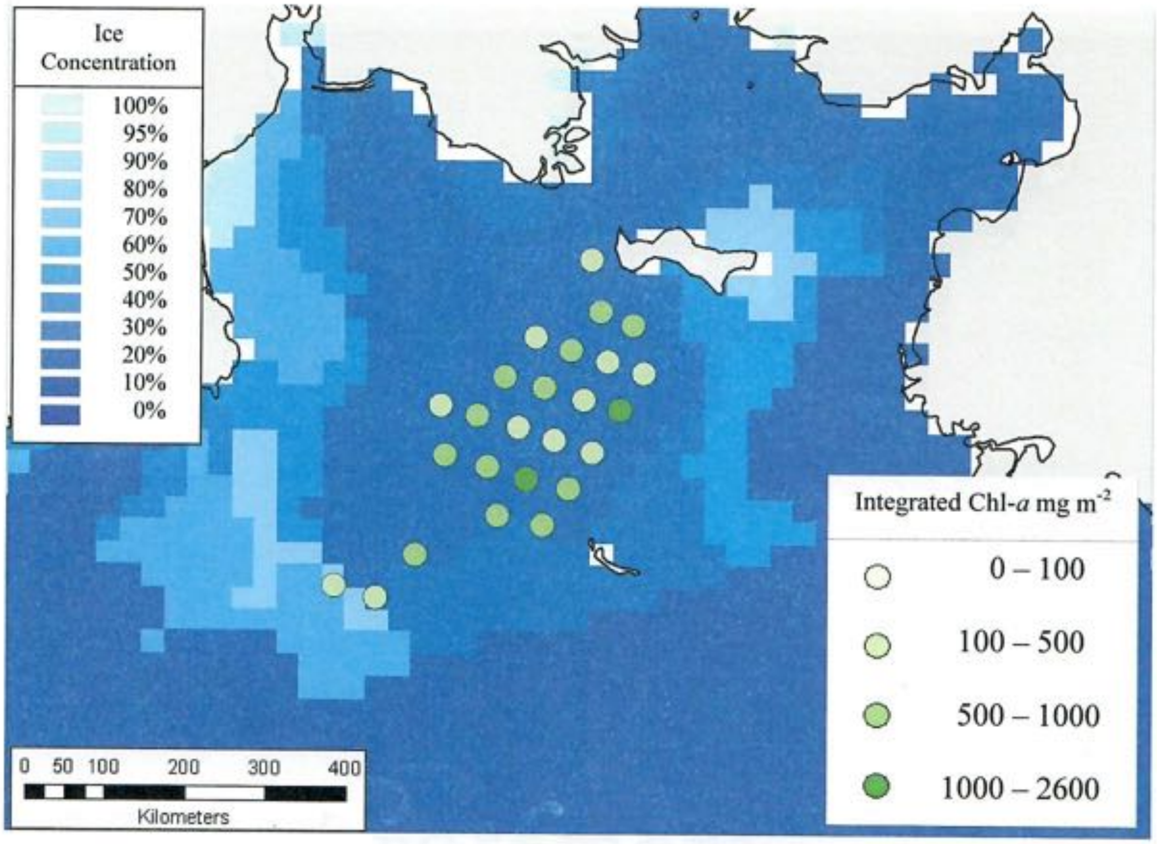


Figure 18. Ice concentration on June 1, 1994 and integrated chl-*a* for stations sampled May 29 – June 4.

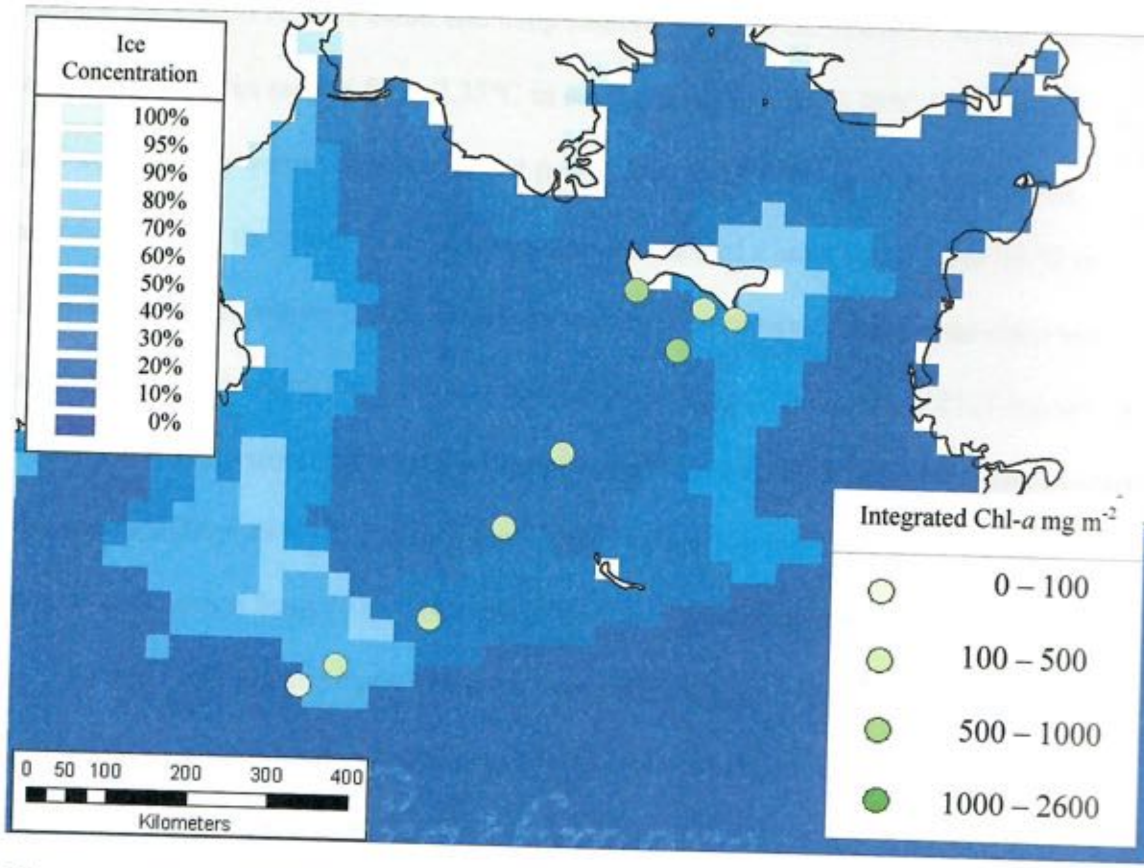


Figure 19. Ice concentration on June 8, 1994 and integrated chl-*a* for stations sampled June 5-8.

shallow stations in Anadyr Strait and deep stations south of St. Matthew Island. Bottom water temperatures ranged from 2.35°C in southern stations to -1.75°C in northern stations. Bottom water salinities ranged from 32.16 to 33.55‰, with higher values nearshore and to the west. Bottom water sigma-t showed a large range from 23.32 to 26.99 g cm^{-3}, with higher values nearshore and in the southwest. Integrated chl-*a* was much higher than winter values and ranged from 38 mg m^{-2} under ice to 2521 mg m^{-2} in recently ice-free waters in the west and southwest (Fig. 14). Sediment chl-*a* values were also much higher (49 – 723 mg m^{-2}) than winter values (up to 17 mg m^{-2}). Faunal abundances ranged from 97 to 6745 individuals m^{-2}. Wet weight biomass ranged from 6 to 1182 g m^{-2} and organic carbon biomass ranged from 0.4 to 39.8 g C m^{-2} (Fig. 15). Sediment oxygen respiration rates ranged from 1.6 to 24.0 mmol O_2 m^{-2} d^{-1}.

3. Ice-melt phytoplankton bloom

Ice-melt began in the western part of SLIP, just prior to sampling, during early-May 1994 (Fig. 16). Figures depicting ice concentration and integrated chl-*a* measurements reveal low chl-*a* under ice and high chl-*a* in recently ice-free waters (Figs. 17, 18, 19). Over time, the bloom seems to decrease, most likely due to depletion of nutrients in surface waters. This is seen in the decrease in chl-*a* concentrations shown on Figs. 18 and 19 versus those in Fig. 17.

4. Sea Surface Temperature

SST after ice-melt was significantly higher along 62°N latitude from 170°W to 180° longitude in 2001 than in 1999 ($p=0.0001$) (Fig. 20). This difference in SST was

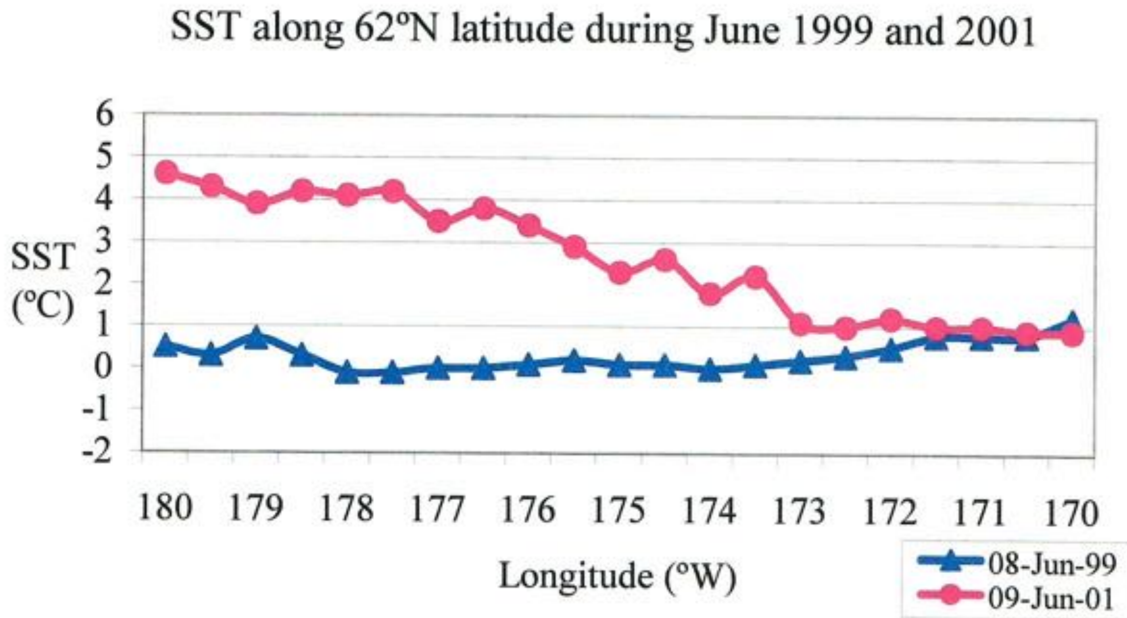


Figure 20. Sea surface temperature along 62°N latitude, spanning 170°W - 180° longitude during early-June 1999 and 2001.

also significant for the entire study region from 61°N to 64°N latitude, 170°W to 180° longitude ($p<0.0001$).

5. Phytoplankton pigment concentration in May and June 1999 and 2001

SeaWIFS data were examined beginning in May of each year to find the first date showing a surface water phytoplankton bloom. A bloom was considered present, when at least one-half of the SLIP region showed at least 1.2 mg m^{-3} chl-*a* in surface water. The value of 1.2 mg m^{-3} was used because it is twice the average surface chl-*a* measured during April 1999. An examination of SeaWIFS data shows a lack of any significant phytoplankton pigment concentration in SLIP until June 14, 1999, when moderate amounts of pigment were detected in the east. Another possible bloom occurred on June 21 in the west (Fig. 21). While neither of these blooms in 1999 met the bloom criteria of at least 1.2 mg m^{-3} over at least one-half of SLIP, these dates were the closest to meeting the criteria. In 2001, phytoplankton pigment concentration was high much earlier in the year (May 15-17) in the central Bering Sea (Fig. 21). Another large-scale bloom occurred over most of the northern Bering Sea from June 5-7. It is important to note that a portion of the pigment concentration detected by the SeaWIFS satellite may be due to sea ice algae, sediment, and reflectance. Thus, it is likely that at least some of the detected water column pigment is not the result of an open water phytoplankton bloom.

6. Correlations between benthic biomass and environmental parameters

Correlation matrices are reported in Appendices D, E, and F for SLIPP01, SLIPP99, and HX177 data respectively. Benthic biomass g C m^{-2} was negatively correlated with bottom water chl-*a*, and not significantly correlated with either integrated

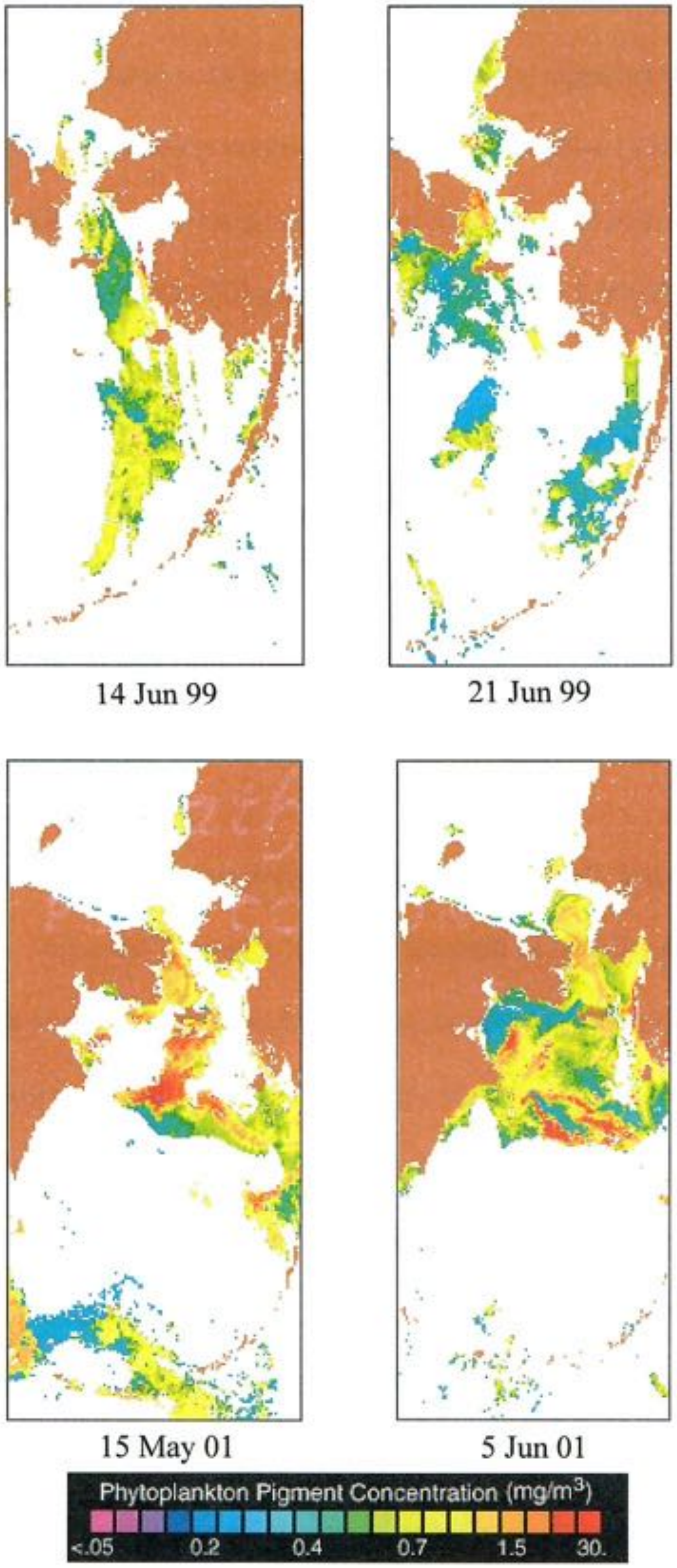


Figure 21. SeaWIFS satellite images of surface phytoplankton pigment concentration.

or sediment chl-*a* in March 2001 (Table 3). In April 1999, benthic biomass g C m^{-2} was once again negatively correlated with bottom water chl-*a*, not significantly correlated with integrated chl-*a*, and positively correlated with sediment chl-*a* (Table 3). In May/June 1994, benthic biomass was positively correlated with bottom water chl-*a* ($p=0.0006$), integrated chl-*a* ($p<0.0001$), and sediment chl-*a* ($p<0.0001$) (Table 3).

7. Correlations between sediment oxygen respiration and environmental parameters

Sediment oxygen respiration mmol m^{-2} d^{-1} was not significantly correlated with chl-*a*, either in water or sediment, in 1999 or 2001 (Table 4). However, in 1994 sediment oxygen respiration was significantly correlated with both bottom water chl-*a* and sediment chl-*a* (Table 4). The correlation with integrated chl-*a* was not significant in 1994.

D. Discussion and conclusions

Chl-*a* values during late-winter/early-spring were relatively low and most likely due to sea ice algae. However, during or just after ice-melt in May/June 1994, there was higher water column production and a tight coupling between the water column and the benthos with significant correlations between benthic biomass and bottom water chl-*a*, integrated water column chl-*a*, and sediment chl-*a* (Table 3).

The time period of ice-melt is important for the stabilization and stratification of the water column (Alexander 1981, Niebauer et al. 1981). These conditions are conducive to high levels of primary production (Niebauer et al. 1995, Stabeno et al. 1998). Work in the southeastern Bering Sea shows that the spring ice-edge bloom accounts for a significant proportion of the annual primary production (Niebauer et al.

Table 3. Spearman's rho correlations between benthic macrofauna organic carbon biomass and environmental parameters. (+ = significant positive correlation at alpha = 0.05, - = significant negative correlation at alpha = 0.05, NS = not significant at alpha = 0.05)

Cruise	Depth	Bottom Salinity	Bottom Temper -ature	Bottom Sigma-t	Bot-tom Chl-*a*	Inte-grated Chl-*a*	Sedi-ment Chl-*a*	Sedi-ment Respi-ration
SLIPP01	+	+	NS	+	-	NS	NS	NS
SLIPP99	+	NS	NS	NS	-	NS	+	NS
HX177	NS	+	-	+	+	+	+	NS

Table 4. Spearman's rho correlations between sediment oxygen respiration and environmental parameters. (+ = significant positive correlation at alpha = 0.05, - = significant negative correlation at alpha = 0.05, NS = not significant at alpha = 0.05)

Cruise	Depth	Bottom Salinity	Bottom Temper-ature	Bottom Sigma-t	Bot-tom Chl-*a*	Inte-grated Chl-*a*	Sedi-ment Chl-*a*	Sedi-ment Respi-ration
SLIPP01	NS	NS	NS	NS	NS	NS	NS	NS
SLIPP99	+	+	-	+	NS	NS	NS	NS
HX177	+	NS	NS	NS	+	NS	+	NS

1981, Stockwell et al. 2001). It is likely that this production exceeds secondary production demands for organic material in the water column and that a large portion sinks, ungrazed to the benthos (Niebauer et al. 1981, Niebauer et al. 1990). A recent study in the SLIP region (Cooper et al. 2002) shows that chl-*a*, both in the water column and sediment, are highest at this time over an annual cycle from April through September.

Lewis et al. (1999) and Itakura et al. (1997) have documented the ability of marine planktonic diatoms and dinoflagellates to survive in sediment for long periods of time (e.g. several months to years). In laboratory experiments, survival was highest at the coldest temperature level (5°C). The large, spring phytoplankton fall-out and long-term survival of cells may provide the food bank necessary to sustain benthic invertebrates throughout times of low production (e.g. late autumn and winter). Therefore, the production generated during this time may be important to ecosystem function throughout the year.

During the transition from winter to spring, the sea surface temperatures rise due to increased day length, higher air temperatures and the disappearance of sea ice. Changes in the timing of the SST rise may affect ecosystem function. Satellite data indicates an early warming of SST following a light ice year. The higher SST in 2001 was likely due to the timing of ice-melt (e.g. ice melted in mid-May 2001 compared to late-May/early-June 1999). The early disintegration of ice allowed solar insolation to heat the surface water earlier in 2001. In addition, it seems reasonable to assume than the relatively thinner ice and reduced ice extent also contributed to an early SST warming. The early SST warming associated with a light ice year could have far-reaching impacts on the northern Bering Sea ecosystem, especially if climate patterns stay in the present warm phase. Organisms with metabolic rates proportional to water temperature, such as zooplankton, will be affected by this change. If zooplankton metabolic and grazing rates rise due to unusually high SST, it is possible that less fresh organic matter will settle to the seafloor following the spring ice-melt bloom.

Chlorophyll data reveal a temporally accelerated open water phytoplankton bloom on May 15, 2001 for SLIP and much of the central Bering Sea (Fig. 21). This bloom region corresponds with the ice concentration and ice thickness maps (Figs. 3, 7), which show a significant ice-melt during the first of May for the same region. Large-scale surface water phytoplankton pigments were not detected until June 14 in the eastern part of SLIP and June 21 in the western part of SLIP for 1999 (Fig. 21). This also corresponds to the timing and pattern of ice-melt with melt beginning first in the east and progressing westward (Fig. 3). The results of the satellite imagery will not be directly compared with shipboard measurements, as direct comparison of satellite data to cruise measurements is out of the scope of this work. Instead, these data are simply used to give an indication of the onset of spring production in surface waters.

IV. Carbon flux model

A. Introduction

In this model, I quantify primary production and carbon deposition to the benthos for the SLIP region over an annual cycle. Integrated chl-*a* data from a number of different cruises were used to define the average annual cycle of water column chl-*a*. Using a previously published equation (Springer & McRoy 1993), integrated chl-*a* was converted to an estimate of primary production. Sediment oxygen respiration data was used to estimate the carbon mineralization rate within the sediment (Grebmeier 1987).

B. Methods

Integrated water column chl-*a* and sediment oxygen respiration data from five cruises (March 2001, April 1999, May/June 1994, June 1993, September 1999) were utilized. Twelve stations in SLIP were selected for use in the model because they were resampled among as many cruises as possible. The model cycle began in spring. The seasonal assumptions and cruises used to define each season are shown in Table 5. Seasonal assumptions were based on biological tracer measurements (e.g. water column chl-*a*) from several cruises over several years. For example, the spring season was estimated to last 21 days because production during May/June 1994 was at an annual high for 21 days during and just after ice-melt. After this 3-week period the water column chl-*a* was much lower and approximated summer time values.

Springer and McRoy (1993) defined an empirical equation for estimating daily carbon productivity from integrated water column chl-*a* applicable to the northern Bering Sea. This equation is given by: $y = -4.55 + 3.92 \log x$, where y = carbon productivity g m^{-2} d^{-1} and x = chlorophyll mg m^{-2}. Integrated chl-*a* values were averaged for each

Table 5. Seasonal assumptions and cruise(s) data used to derive seasonal averages.

Season	Cruise(s)	Time period	Number of days
Spring	May/June 1994	mid-May – early-Jun	21
Summer	Jun 1993	early-Jun – mid-Aug	72
Fall	Sept 1999	mid-Aug - Sept	46
Winter	Mar 2001, Apr 1999	Oct – mid-May	226

season and placed into the equation to obtain carbon productivity g C m^{-2} d^{-1}. Because the equation used by Springer and McRoy (1993) was based on summer chl-*a* and primary productivity values, I estimated that autumn carbon productivity was 50% of summer productivity because of decreased light levels during this season. Winter productivity was estimated to be zero in this model because sea ice algal production contributes considerably less to annual production relative to water column production (Springer & McRoy 1993). A phytoplankton sinking velocity of 10 m d^{-1} was used following the methods of Walsh et al. (1989) and an average bottom depth of 50 m was used in the model.

Benthic carbon consumption was derived from total sediment oxygen uptake using a respiratory quotient (RQ) = 1. This RQ value was used to convert oxygen uptake to carbon consumption (Grebmeier 1987). Benthic carbon consumption values were averaged for each season using the same seasonal definitions as were used in estimated carbon production. The following formula was used to convert benthic carbon mineralization mmol C m^{-2} d^{-1} to benthic carbon consumption g C m^{-2} $season^{-1}$: seasonal benthic carbon consumption = mean daily benthic carbon mineralization mmol C m^{-2} d^{-1} X number of days in season X 0.012 g C/mmol C. All data were input into a software modeling program, STELLA II® version 3.0.6 (High Performance Systems, Hanover, New Hampshire). A schematic diagram of stocks, flows, and converters is illustrated in Figure 22.

C. Results

Model output over an annual cycle assuming no export of carbon from the system shows an excess of carbon production over benthic consumption (Fig. 23). Annual

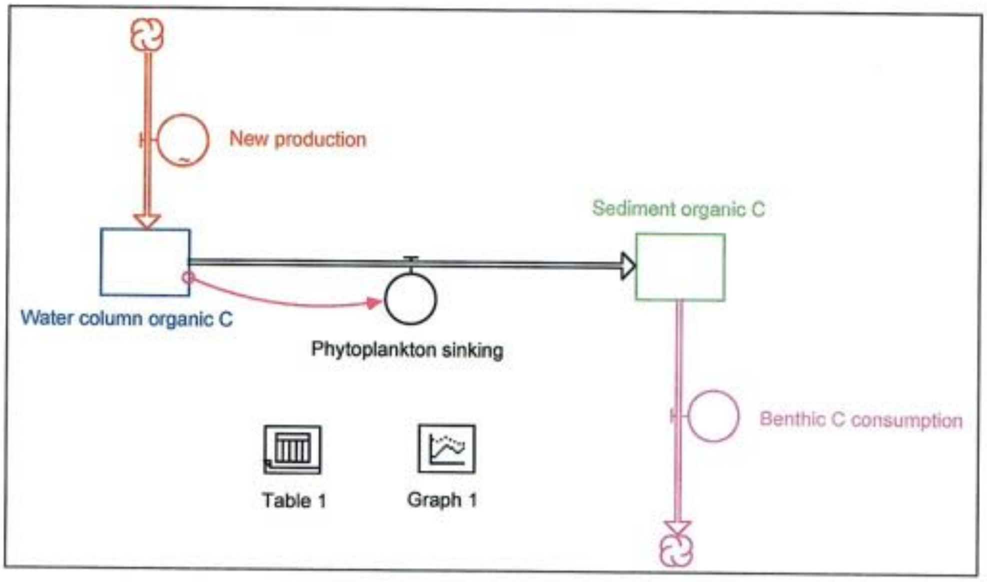


Figure 22. Schematic diagram of stocks, flows, and converters for carbon flux model.

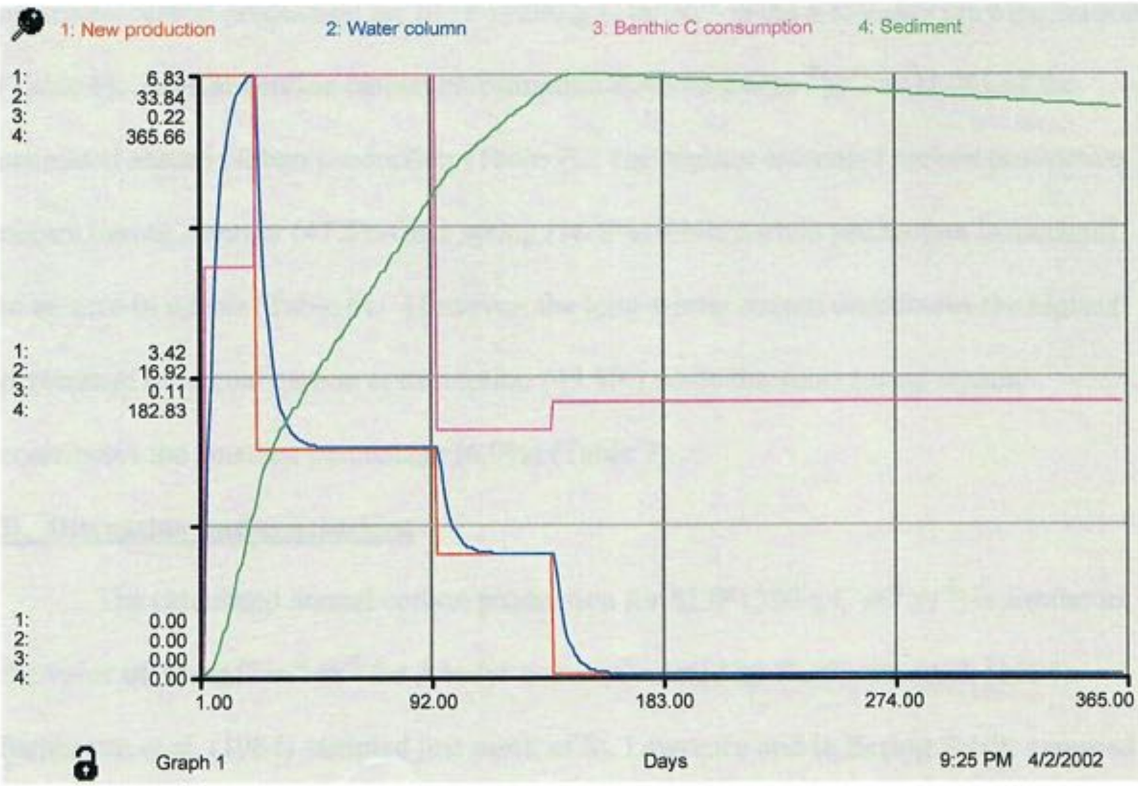


Figure 23. Model output for 3 parameters: 1. New production g C m^{-2} d^{-1}, 2. Water column standing stock production g C m^{-2}, 3. Benthic carbon consumption g C m^{-2} d^{-1}, 4. Sediment standing stock production g C m^{-2}.

estimated carbon production for SLIP is 390 g C m^{-2} yr^{-1} using a 139-day growing season (Table 6). Annual benthic carbon consumption is 45.73 g C m^{-2} yr^{-1} or 11.7% of the estimated annual carbon production (Table 7). The highest estimated carbon production occurs during summer (47.3%) and spring (36.8%) while carbon production is assumed to be zero in winter (Table 6). However, the long winter season contributes the highest percentage of annual carbon consumption (49.4%) while the short spring season contributes the smallest percentage (6.9%) (Table 7).

D. Discussion and conclusions

The calculated annual carbon production for SLIP (390 g C m^{-2} yr^{-1}) is similar to the value of 324 g C m^{-2} yr^{-1} for Anadyr water calculated by Sambrotto et al. (1984). Sambrotto et al. (1984) sampled just north of St. Lawrence and in Bering Strait, assumed a growing season from June through September, and used an estimated primary production of 2.7 g C m^{-2} d^{-1}. Walsh et al. (1989) reported an annual primary production of 300 g C m^{-2} d^{-1} for Anadyr and Bering Strait waters using a 150-day growing season and a daily primary production of 2.0 g C m^{-2} d^{-1}. My study has a higher annual carbon production estimate, which may be due to the incorporation of the spring ice-melt bloom. The spring season contributed 36.8% of the annual carbon production in only 21 days. However, it is important to note that at least some of the water column chl-*a* detected in spring is likely due to sea ice algae. Species composition was not preformed during these cruises, therefore a summary of open water species and sea ice algal species is not possible. Limitations of the equation used and interannual variability also introduce some uncertainty into this evaluation. Springer & McRoy (1993) calculated 470, 480,

Table 6. Daily, seasonal, and seasonal percent of annual estimated carbon production.

Season	Estimated carbon production $g\ C\ m^{-2}\ d^{-1}$	Estimated carbon production $g\ C\ m^{-2}\ season^{-1}$	Seasonal carbon production % of annual
Spring	6.83	143.43	36.8%
Summer	2.56	184.32	47.3%
Fall	1.36	62.56	16.0%
Winter	0.00	0.00	0.0%
Total	--	390.31	100.0%

Table 7. Daily, seasonal, and seasonal percent of annual estimated benthic carbon consumption.

Season	Benthic carbon consumption $g\ C\ m^{-2}\ d^{-1}$	Benthic carbon consumption $g\ C\ m^{-2}\ season^{-1}$	Seasonal benthic carbon consumption % of annual
Spring	0.15	3.15	6.9%
Summer	0.22	15.84	34.6%
Fall	0.09	4.14	9.1%
Winter	0.10	22.60	49.4%
Total	--	45.73	100.0%

and 456 g C m^{-2} yr^{-1} for the Chukchi Sea, Chirikov Basin, and Gulf of Anadyr respectively. Growing seasons were 100, 120, and 120 days with average productivities of 4.7, 4.0, and 3.8 g C m^{-2} d^{-1}. While it is possible that my study overestimated annual carbon production, these data are similar to the calculated yearly carbon production in SLIP.

The calculated annual benthic carbon consumption for SLIP (45.73 g C m^{-2} yr^{-1}) is similar to the values of 67.8 g C m^{-2} yr^{-1} (Bering Shelf/Anadyr water) and 27.8 g C m^{-2} yr^{-1} (Alaska Coastal water) calculated by Grebmeier (1987). My model shows that 11.7% of the estimated annual carbon production is consumed by macrofauna, meiofauna, microfauna, and microbes living within the sediment. Assuming no consumption by zooplankton, this leaves 344.27 g C m^{-2} yr^{-1} for export or burial within the sediment.

Because ice-mel in SLIP typically occurs before ice -melt in the Chirikov Basin and Bering Strait, it is probable that spring production begins in SLIP first. Due to the prevalent northward current flow, it is likely that a significant amount of SLIP production, especially during spring, reaches the Chirikov Basin and Bering Strait. It is possible that this production is important for seeding the water column prior to or during ice-melt.

V. Conclusions and summary

1. Does variation in winter ice cover characteristics affect water column and sediment parameters during winter and/or spring?

Late-winter/early-spring 1999 measurements of water column and sediment chl-*a* revealed low concentrations of pigment ranging from 9.4–78.2 mg m^{-2} in water and 4.2-13.4 mg m^{-2} in sediment. Late-winter measurements in 2001 of water column and sediment chl-*a* were similar in range to 1999. Water column chl-*a* ranged from 3.1 to 52.3 mg m^{-3} and sediment chl-*a* ranged from 0.12-17.05 mg m^{-2}. The Wilcoxon Signed Rank Test shows that measurements of integrated water column and sediment chl-*a* were not significantly different in March 2001 and April 1999, in spite of the fact that winter ice cover was greatly reduced in 2001 and unusually heavy in 1999. Low light levels and a mixed water column limit production in the winter. Production is possible in the late-winter and early-spring as light returns to the system and ice-melt supports water column stability, thus initiating primary production.

In spring, however, satellite images of phytoplankton pigment concentration reveal a temporal acceleration of surface water production in spring 2001. A large-scale bloom was detected on May 15 for the area corresponding to the origin of ice-breakup, which occurred around May 5. Surface florescence was not detected until June 14 for the eastern and June 21 for the western part of SLIP following the heavy ice of 1999.

2. Does the timing of ice-melt affect water column and sediment parameters?

During late-winter/early-spring sampling, relatively low chl-*a* concentrations were detected, even under the reduced ice conditions during March 2001. The same storm events that impeded ice production likely created a mixed water column that was unable to support production. However, water column and sediment chl-*a* values obtained in May/June 1994 during and just after ice-melt were much higher. This and other studies show that these chl-*a* concentrations are at a maximum over an annual cycle from March to September (Grebmeier & Cooper 1995, Cooper et al. 2002). The model predicts that the spring ice-melt bloom contributes a significant amount (36.8%) of the annual carbon production. Work in the southeastern Bering along the ice edge in April, May, and June 1975-1977, corroborated the importance of the ice-melt bloom over an annual cycle (Niebauer et al. 1981).

Many authors have described the pattern of ice-melt and a subsequent phytoplankton bloom in spring as the ice edge retreats in the Bering Sea (McRoy & Goering 1974, Alexander 1981, Niebauer et al. 1981, Niebauer et al. 1990). Factors influencing the bloom include light availability and water column stratification and stability. The large bloom detected in spring 1994 likely provided a large supply of carbon to the benthos because pelagic zooplankton grazers did not have adequate time to take advantage of the intense burst of food. Also, previous studies show that cold water temperatures inhibit many zooplankton grazers during spring ice-melt in the northern Bering Sea (Cooney 1977, Cooney 1981). This scenario is supported by high sediment chl-*a* measurements observed during the cruise in 1994 (Cooper et al. 2002).

Stabeno and Overland (2001) show a trend of reduced ice in the Bering Sea in the last two decades. While there was a slight increase in ice extent from 1989-98, the overall trend has been a decline since 1976. This study also notes that under reduced ice coverage, the timing of the winter-spring transition is earlier during the year. In my study, 1999 can be used as an example of pre-1976 conditions and 2001 as post-1976. Using this scenario, during 2001, late ice formation, thin ice, and early melt contribute to a shortening of the winter season and an earlier spring transition. Results show a temporal acceleration of primary production and an early warming of SST. Benthic organisms are accustomed to an annual cycle of food availability, temperature, and salinity. If the transition between winter and spring continues to be earlier in the year, then the metabolic cycles of benthic organisms may become disrupted. If much of the annual food supply, largely resulting from the spring phytoplankton bloom, is deposited earlier in the year, then these organisms may not be able to process the food because of metabolic reasons. When physical oceanic processes change, marine organisms must be able to adapt. While benthic organisms may be able to adapt to changes in physical processes by relocating to suitable habitat, they cannot change the timing and amount of food that settles out from the overlying water column.

List of References

List of References

Abacus Concepts, Inc.© 1995. Statview 4.5 for Macintosh.™ Berkeley, CA

Alexander V (1981) Ice-biota interactions: an overview. In: Hood DW, Calder JA (eds.) The eastern Bering Sea shelf: oceanography and resources, Vol 2. University of Washington Press, Seattle, p. 757-762

Alexander V, Chapman T (1981) The role of epontic algal communities in Bering sea ice. In: Hood DW, Calder JA (eds.) The eastern Bering Sea shelf: oceanography and resources, Vol 2. University of Washington Press, Seattle, p.773-780

Arrigo K, Worthen DL, Dixon P, Lizotte MP (1998) Primary production of near surface communities within Antarctic pack ice. In: Lizotte MP, Arrigo KR (eds.) Antarctic sea ice biological processes, interactions, and variability. Antarctic Research Series Vol. 73, American Geophysical Union, Washington, DC. p. 23-43

Banks H, Wood R (2002) Where to look for anthropogenic climate change in the ocean. Journal of Climate 15:879-891

Brodeur RD, Mills CE, Overland JE, Walters GE, Schumacher JD (1999) Evidence for a substantial increase in gelatinous zooplankton in the Bering Sea, with possible links to climate change. Fisheries Oceanography 8:296-306

Burns JJ, Shapiro LH, Fay FH (1981) Ice as a marine mammal habitat in the Bering Sea. In: Hood DW, Calder JA (eds.) The eastern Bering Sea shelf: oceanography and resources, Vol 2. University of Washington Press, Seattle, p. 781-798

Clarke A (1980) A reappraisal of the concept of metabolic cold adaptation in polar marine invertebrates. Biological Journal of the Linnean Society 14:77-92

Comiso JC (1995) Satellite remote sensing of the Arctic Ocean and adjacent seas. In: Smith WO, Grebmeier JM (eds.) Arctic oceanography: marginal ice zones and continental shelves. American Geophysical Union. p. 1-50. Washington DC

Cooney RT (1977) Zooplankton and micronekton studies in the Bering-Chukchi/Beaufort Seas. In: Environmental assessment of the Alaskan continental shelf. NOAA/Outer Continental Shelf Assessment Program (OCSEAP), Annual Report 10:275-363

Cooney RT (1981) Bering sea zooplankton and micronekton communities with emphasis on annual production. In: Hood DW, Calder JA (eds.) The eastern Bering Sea shelf: oceanography and resources, Vol 2. University of Washington Press, Seattle, p. 947-974

Cooper LW, Grebmeier JM, Larsen IL, Egorov VG, Theodorakis C, Kelly HP, Lovvorn JR (2002) Seasonal variation in water column processes and sedimentation of organic materials in the St. Lawrence Island polynya region, Bering Sea. Marine Ecology Progress Series 226:13-26

Cota GF, Horne EPW (1989) Physical control of arctic ice algal production. Marine Ecology Progress Series 52:111-121

Cota GF, Prinsenberg SJ, Bennett EB, Loder JW, Lewis MR, Anning JL, Watson NHF, Harris, LR (1987) Nutrient fluxes during extended blooms of Arctic ice algae. Journal of Geophysical Research 92:1951-1962

Cota GF, Sullivan CW (1990) Photoadaptation, growth, and production of bottom ice algae in the Antarctic. Journal of Phycology 26:399-411

Duffy PB, Eby M, Weaver AJ (2001) Climate model simulations of effects of increased atmospheric CO_2 and loss of sea ice on ocean salinity and tracer uptake. Journal of Climate 14:520-532

Environmental Working Group Joint U.S. Russian Sea Ice Atlas (2000) Distributed by the National Snow and Ice Data Center, Boulder, CO, USA

ESRI® (2000) ArcInfo 8.0 Redlands, CA (http://www.esri.com)

Fay FH (1974) The role of ice in the ecology of marine mammals of the Bering Sea. In: Hood DW, Kelley EJ (eds.) Oceanography of the Bering Sea with emphasis on renewable resources. Institute of Marine Sciences, University of Alaska, Fairbanks, p. 383-399

Fay FH, Feder HM, Stoker SW (1977) An estimation of the impact of the Pacific walrus population on its food resources in the Bering Sea. Marine Mammal Commission, Washington, DC, 1977

Feder HM, Jewett SC (1981) Feeding interactions in the eastern Bering Sea with emphasis on the benthos. In: Hood DW, Calder JA (eds.) The eastern Bering Sea shelf: oceanography and resources, Vol 2. University of Washington Press, Seattle, p 1229 – 1261

Goddard Distributed Active Archive Center (DAAC) – SeaWIFS, Greenbelt MD (http://daac.fsfc.nasa.gov/data/dataset/SEAWIFS/index.html)

Grebmeier JM (1987) The ecology of benthic carbon cycling in the northern Bering and Chukchi Seas, Ph.D. thesis, 185 pp., Univ. of Alaska, Fairbanks

Grebmeier JM, Cooper LW (1995) Influence of the St. Lawrence Island Polynya upon the Bering Sea benthos. Journal of Geophysical Research 100:4439-4460

Grebmeier JM, Dunton KH (2000) Benthic processes in the northern Bering/Chukchi

Seas: Status and global change. In: Huntington HP (ed.) Impacts of changes in sea ice and other environmental parameters in the Arctic. Report of the Marine Mammal Commission Workshop, 15-17 February 2000, Girdwood, Alaska

Grebmeier JM, McRoy CP, Feder, HM (1988) Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas. I. Food supply source and benthic biomass. Marine Ecology Progress Series 48: 57-67

Grebmeier JM, Smith WO, Conover RJ (1995) Biological processes on Arctic continental shelves: ice-ocean-biotic interactions. In: Smith WO and Grebmeier JM (eds.) Arctic oceanography: marginal ice zones and continental shelves. American Geophysical Union, Washington DC, p. 231-261

Grotefendt K, Logemann K, Quadfasel D, Ronski S (1998) Is the Arctic Ocean warming? Journal of Geophysical Research 103:27,679-27,687

Hare SR, Mantua NJ (2000) Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103-145

Hare SR, Minobe S, Wooster WS, McKinnell S (2000) An introduction to the PICES symposium on the nature and impacts of North Pacific climate regime shifts. Progress in Oceanography 47:99-102

High Performance Systems, Inc. 1994. STELLA II® v. 3.0.6. Hanover, NH (http://www.hps-inc.com/)

Highsmith RC, Coyle KO (1992) Productivity of arctic amphipods relative to gray whale energy requirements. Marine Ecology Progress Series 83:141-150

Hunt GL, Baduini CL, Brodeur RD, Coyle KO, Kachel NB, Napp JM, Salo SA, Schumacher JD, Stabeno PJ, Stockwell DA, Whitledge TE, Zeeman SI (1999)

The Bering Sea in 1998: the second consecutive year of extreme weather-forced anomalies. Eos, Transactions, American Geophysical Union 80:561-566

Itakura S, Imai I, Itoh K (1997) "Seed bank" of coastal planktonic diatoms in bottom sediments of Hiroshima Bay, Seto Inland Sea, Japan. Marine Biology 128:497-508

Izrael YA, Tsyban AV, Whitledge TE, McRoy CP, Shigaev VV (1992) Polar Marine Ecosystems and Climate. In: Nagel PA (ed.) Results of the Third Joint US-USSR Bering & Chukchi Seas Expedition (BERPAC), Summer 1988. US Fish and Wildlife Service, Washington, DC. p. 7-11

Legendre L, Ackley SF, Dieckmann GS, Bullicksen B, Horner R, Hoshiai T, Melnikov IA, Reeburgh WS, Spindler M, Sullivan CW (1992) Ecology of sea ice biota: 2. global significance. Polar Biology 12:429-444

Lewis J, Harris ASD, Jones KJ, Edmonds RL (1999) Long-term survival of marine planktonic diatoms and dinoflagellates in stored sediment samples. Journal of Plankton Research 21:343-354

McGowan JA, Cayan DR, Dorman LM (1998) Climate-ocean variability and ecosystem response in the Northeast Pacific. Science 281:210-217

McNutt SL (1981) Ice conditions in the eastern Bering Sea from NOAA and LANDSAT imagery: winter conditions 1974, 1976, 1977, 1979. NOAA Tech. Memo. ERL PMEL-24, 179 pp. [NTIS PB81-220188]

McRoy CP, Goering JJ (1974) The influence of ice on the primary productivity of the Bering Sea. In: Hood DW, Kelley EJ (eds.) Oceanography of the Bering Sea with emphasis on renewable resources. Institute of Marine Sciences, University of

Alaska, Fairbanks, p. 403-421

Muench RD, Ahlnäs K (1976) Ice movement and distribution in the Bering Sea from March to June 1974. Journal of Geophysical Research 81:4467-4476

Nelson FE, Anisimov OA, Shiklomanov NI (2002) Climate change and hazard zonation in the circum-Arctic permafrost region. Natural Hazards 26:203-225

Niebauer HJ (1981) Recent fluctuations in sea ice distribution in the eastern Bering Sea. In: Hood DW, Calder JA (eds.) The eastern Bering Sea shelf: oceanography and resources, Vol 1. University of Washington Press, Seattle, p. 133-140

Niebauer HJ, Alexander V, Cooney RT (1981) Primary production at the eastern Bering Sea ice edge: the physical and biological regimes. In: Hood DW, Calder JA (eds.) The eastern Bering Sea shelf: oceanography and resources, Vol 2. University of Washington Press, Seattle, p. 763-772

Overland JE (1981) Marine climatology of the Bering Sea. In: Hood DW, Calder JA (eds.) The eastern Bering Sea shelf: oceanography and resources, Vol 1. University of Washington Press, Seattle, p. 15-22

Overland JE, Pease CH (1982) Cyclone climatology of the Bering Sea and its relation to sea ice extent. Monthly Weather Review 110:5-13

Pease CH (1980) Eastern Bering Sea ice processes. Monthly Weather Review 108:2015-2023

Perovich DK, Cota GF, Maykut GA, Grenfell TC (1993) Bio-optical observations of first-year arctic sea ice. Geophysical Research Letters 20:1059-1062

Peterson MR, Larned WW, Douglas DC (1999) At-sea distribution of Spectacled Eiders: A 120-year-old mystery resolved. The Auk 116:1009-1020

Peterson MR, Piatt JF, Trust KA (1998) Foods of spectabled eiders (*Somateria fischeri*) in the Bering Sea, Alaska. Wildfowl 49:124-128

Pickard GL (1975) Descriptive physical oceanography. Pergamon Press, Elmsford, New York, pp. 214

Radchenko VI, Khen GV, Slabinsky AM (2001) Cooling in the western Bering Sea in 1999: Quick propagation of the La Niña signal or compensatory processes effect? Progress in Oceanography 49:407-422

Rothrock DA, Yu Y, Maykut GA (1999) Thinning of the Arctic Sea-Ice Cover. Geophysical Research Letters 26:3469-3472

Rysgaard S, Nielson TG, Hansen BW (1999) Seasonal variation in nutrients, pelagic primary production and grazing in a high-Arctic coastal marine ecosystem, Young Sound, Northeast Greenland. Marine Ecology Progress Series 179:13-25

Satellite Active Archive website administered by the National Oceanic and Atmospheric Administration (NOAA), Washington DC (http://www.saa.noaa.gov)

Schumacher JD, Aagaard K, Pease CH, Tripp RB (1983) Effects of a shelf polynya on flow and water properties in the northern Bering Sea. Journal of Geophysical Research 88: 2723-2732

Springer AM, McRoy CP (1993) The paradox of pelagic food webs in the northern Being Sea. III. Patterns of primary production. Continental Shelf Research 13:575-599

Smith REH, Anning J, Clement P, Cota G (1988) Abundance and production of ice algae in Resolute Passage, Canadian Arctic. Marine Ecology Progress Series 48:251-263

Stabeno PJ, Overland JE (2001) Bering Sea shifts toward an earlier spring transition.

EOS, Transactions, American Geophysical Union 82:317-321

Stehn RA, Dau CP, Conant B, Butler WI Jr. (1993) Decline of spectacled eiders nesting in western Alaska. Arctic 46:264-277

Stringer WJ, Groves JE (1991) Location and areal extent of polynyas in the Bering and Chukchi Seas. Arctic 44, 164-171

Stoker SW (1978) Benthic invertebrate macrofauna of the eastern continental shelf of the Bering/Chukchi Seas, Ph.D. thesis 253 pp., Univ. of Alaska, Fairbanks, 1978

Stoker SW (1981) Benthic invertebrate macrofauna of the eastern Bering/Chukchi continental shelf. In: Hood DW, Calder JA (eds.) The eastern Bering Sea shelf: oceanography and resources, Vol 2. University of Washington Press, Seattle, p. 1069-1090

Stockwell DA, Whitledge TE, Zeeman SI, Coyle KO, Napp JM, Brodeur RD, Pinchuk AI, Hunt GL (2001) Anomalous conditions in the south-eastern Bering Sea, 1997: nutrients, phytoplankton and zooplankton. Fisheries Oceanography 10:99-116

Thomas DN, Lara RJ, Haas C, Schnack-Schiel SB, Dieckmann GS, Kattner G, Nöthig EM, Mizdalski E (1998) Biological soup within decaying summer sea ice in the Amundsen Sea, Antarctica. In: Lizotte MP, Arrigo KR (eds.) Antarctic sea ice biological processes, interactions, and variability. Antarctic Research Series Vol. 73, American Geophysical Union, Washington DC, p. 161-171

Thompson DW, Wallace JM (2000) Annular modes in the extratropical circulation, Part I, month-to-month variability. Journal of Climate 13:1000-1016

Trenberth KE, Hurrell JW (1994) Decadal atmosphere-ocean variations in the Pacific. Climate Dynamics 9:303-319

U.S. National Ice Center, Washington DC (www.natice.noaa.gov)

U.S. National Weather Service (www.nws.noaa.gov)

Vance TC, Schumacher JD, Stabeno PJ, Baier CT, Wyllie-Echeverria T, Tynan CT, Brodeur RD, Napp JM, Coyle KO, Becker MB, Hunt GL, Stockwell D, Whitledge TE, Jump M, Zeeman S (1998) Aquamarine waters recorded for first time in eastern Bering Sea. Eos, Transactions, American Geophysical Union 79:121-126

Vinnikov KY, Robock A, Stouffer RJ, Walsh JE, Parkinson CL, Cavalieri DJ, Mitchell JFB, Garrett D, Zakharov VF (1999) Global warming and Northern Hemisphere sea ice extent. Science 286:1934-1937

Voss R, Mikolajewicz U (2002) Long-term climate changes due to increased CO_2 concentration in the coupled atmosphere-ocean general circulation model ECHAM3/LSG. Climate Dynamics 17:45-60

Walsh JE, Johnson CM (1979) An analysis of arctic sea ice fluctuations, 1953-77. Journal of Physical Oceanography 9:580-591

Walsh JJ, McRoy CP, Coachman LK, Goering JJ, Nihoul JJ, Whitledge TE, Blackburn TH, Parker PL, Wirick CD, Shuert PG, Grebmeier JM, Springer AM, Tripp RD, Hansell DA, Djenidi S, Deleersnijder E, Henriksen K, Lund BA, Andersen P, Müller-Karger FE, Dean K (1989) Carbon and nitrogen cycling within the Bering/Chukchi Seas: source regions for organic matter effecting AOU demands of the Arctic Ocean. Progress in Oceanography 22:277-359

Washington WM, Weatherly JW, Meehl GA, Semtner AJ, Bettge TW, Craig AP, Strand WG, Arblaster J, Wayland VB, James R, Zhang Y (2000) Parallel climate model

(PCM) control and transient simulations. Climate Dynamics 16:755-774

Weatherly JW, Bitz C (2001) Natural and Anthropogenic Climate Change in the Arctic. 12th Symposium on Global Change and Climate Variations, 15-18 Jan. 2001, Albuquerque, American Meterological Society, Boston

Wyllie-Echeverria T, Wooster TS (1998) Year-to-year variations is Bering Sea ice cover and some consequences for fish distributions. Fisheries Oceanography 7:159-170

Appendices

Appendix A.

HX177 Station information

Station Number	Station Name	Date	Latitude	Longitude
45	NEC9	05/24/94	59.868	-174.851
46	SEC9	05/24/94	60.033	-175.766
47	SEC8	05/24/94	60.417	-175.001
48	SIL8	05/25/94	60.551	-175.885
49	SWC7	05/25/94	61.167	-175.833
50	NWC7	05/25/94	61.267	-176.751
51	NWC8	05/26/94	60.784	-177.617
52	DLN8	05/26/94	60.906	-178.416
53	DLN7	05/26/94	61.401	-177.483
54	DLN6	05/26/94	61.771	-176.799
55	DLN5	05/26/94	62.166	-176.016
56	DLN4	05/27/94	62.516	-175.301
57	DLN3	05/27/94	62.902	-174.583
58	DLN2	05/27/94	63.267	-173.783
59	DLN1	05/27/94	63.584	-173.053
60	NWC2	05/27/94	63.117	-173.085
61	NWC3	05/28/94	62.765	-173.830
62	NWC4	05/28/94	62.399	-174.582
63	NWC5	05/28/94	62.036	-175.250
64	NWC6	05/28/94	61.666	-175.999
65	SWC6	05/29/94	61.516	-175.133
66	SIL6	05/29/94	61.366	-174.332
67	SWC5	05/29/94	61.881	-174.399
68	SWC4	05/29/94	62.250	-173.763
69	SWC3	05/29/94	62.599	-173.085
70	SWC2	05/30/94	62.950	-172.333
71/72	SIL2	05/30/94	62.767	-171.664
73	SIL3	05/30/94	62.433	-172.333
74	SEC3	05/30/94	62.269	-171.584
75	SEC4	05/30/94	61.934	-172.201
76	SIL4	05/31/94	62.080	-172.936
77	SIL5	05/31/94	61.716	-173.671
78	SEC6	05/31/94	61.216	-173.483
79	SEC7	05/31/94	60.881	-174.087

Appendix A. Continued.

Station Number	Station Name	Date	Latitude	Longitude
80	SIL7	06/01/94	61.017	-175.000
81	SWC8	06/01/94	60.682	-176.750
82	SWC9	06/01/94	60.267	-177.583
83	NWC9	06/02/94	60.399	-178.417
84	SIL4	05/31/94	61.367	-174.334
85	SEC5	06/03/94	61.550	-172.900
86	SWC5	05/29/94	61.882	-174.400
87	NWC5	05/28/94	62.035	-175.248
88	DLN5	06/03/94	62.165	-176.018
89	DLN4	05/27/94	62.515	-175.299
90	NWC3	06/04/94	62.765	-173.831
91	NWC1	06/04/94	63.482	-172.382
92	SIL1	06/04/94	63.166	-170.916
93	SWC1	06/05/94	63.282	-171.682
101	SEC1	06/06/94	62.999	-170.249
102	SECX	06/06/94	62.851	-169.596
103	SEC2	06/06/94	62.617	-170.947
104	SIL5	06/06/94	61.714	-173.669
105	SIL7	06/07/94	61.016	-175.000
106	SIL9	06/07/94	60.133	-176.618
107/108	SWC10	06/07/94	59.685	-178.502

Appendix B.

SLIPP99 Station Information

Station Number	Station Name	Date	Latitude	Longitude
1	VNG1	04/13/99	62.013	-175.056
2	NWC5	04/13/99	62.051	-175.207
3	DLN4	04/14/99	62.512	-175.294
4	DLN3	04/15/99	62.893	-174.589
5	DLN2	04/16/99	63.286	-173.783
6	NWC2	04/16/99	63.289	-173.790
7	NWC2.5	04/17/99	63.025	-173.457
8	NWC3	04/17/99	62.778	-173.861
9	NWC4A	04/17/99	62.563	-174.195
10	VNG3	04/18/99	62.558	-173.831
11	SWC4A	04/18/99	62.421	-173.417
12	SWC3	04/18/99	62.584	-173.078
13	POP4	04/18/99	62.403	-172.687
14	POP3A	04/19/99	62.566	-172.301
15	SWC3A	04/19/99	62.759	-172.704
16	VNG4	04/19/99	62.757	-173.413
17	VNG5	04/20/99	62.977	-173.005
18	SWC2	04/20/99	62.932	-172.301
20	VNG3.5	04/21/99	62.563	-173.556
22	ROM1	04/21/99	63.087	-171.475
23	H1	04/22/99	63.119	-172.187
25	NWC4	04/23/99	62.394	-174.570
26	NWC4A	04/23/99	62.324	-174.183
27	SWC4	04/24/99	62.248	-173.754
28	SWC5	04/24/99	61.881	-174.382
29	SIL5	04/24/99	61.715	-173.606
30	SIL4	04/25/99	62.079	-172.937
31	SIL3	04/25/99	62.440	-172.309
32	SEC3	04/25/99	62.280	-171.573
33	NEC3	04/26/99	62.299	-170.631
34	NEC4	04/26/99	61.776	-171.316
35	SEC4	04/26/99	61.928	-172.212
36	SEC5	04/27/99	61.562	-172.918
37	NEC5	04/27/99	61.380	-171.946

Appendix C.

SLIPP01 Station Information

Station Number	Station Name	Date	Latitude	Longitude
9	VNG1	03/17/01	62.016	-175.059
10	NWC 5	03/18/01	62.056	-175.201
11	DLN4	03/18/01	62.511	-175.293
12	DLN3	03/18/01	62.892	-174.089
13	DLN2	03/19/01	63.275	-173.754
14	NWC2	03/19/01	63.108	-173.122
15	NWC2.5	03/20/01	63.026	-173.474
16	NWC3	03/20/01	62.782	-173.871
17	NWC4A	03/20/01	62.566	-174.181
18	NWC4	03/20/01	62.400	-174.578
19	VNG3	03/20/01	62.560	-173.839
20	VNG4	03/22/01	62.758	-173.426
21	VNG5	03/22/01	62.971	-172.999
22	SWC2	03/22/01	62.929	-172.289
23	SWC3A	03/22/01	62.756	-172.714
24	SWC3	03/22/01	62.582	-173.069
25	SWC4A	03/23/01	62.417	-173.434
26	NWC4A1	03/23/01	62.325	-174.184
27	SWC4	03/23/01	62.251	-173.736
28	SWC5	03/23/01	61.886	-174.376
29	SIL5	03/24/01	61.718	-173.608
30	SIL4	03/24/01	62.086	-172.948
31	POP4	03/24/01	62.406	-172.691
32	SIL3	03/24/01	62.436	-172.310
33	POP3A	03/24/01	62.568	-172.303
34	SIL2	03/26/01	62.762	-171.661
35	SEC2	03/27/01	62.615	-170.948
36	SEC3	03/27/01	62.285	-171.571
37	SEC4	03/27/01	61.936	-172.210
38	SEC5	03/28/01	61.563	-172.906
39	NEC5	03/28/01	61.384	-171.951
40	NEC4	03/28/01	61.780	-171.310
41	NEC3	03/29/01	62.067	-170.625
42	NEC2	03/29/01	62.431	-170.074
43	NEC2.5	03/30/01	62.467	-170.939
44	SEC2.5	03/30/01	62.494	-171.844
45	VNG3.5	03/31/01	62.575	-173.566

Appendix C. Continued.

Station Number	Station Name	Date	Latitude	Longitude
46	CD1	03/31/01	62.681	-173.375
47	NWC1.5	04/01/01	63.338	-172.917
48	NWC1.7	04/01/01	63.428	-173.129
49	DLN1.5	04/01/01	63.483	-173.233
50	NWC 1.6	04/01/01	63.381	-173.003

Appendix D.

Correlation matrix for SLIPP01 (see example cell below). Numbers is **bold** are significant at alpha=0.05. A table below explains abbreviations used in this and all other correlation matrices.

	Depth	Bot Sal	Bot T	Bot Sig	Bot Chl	Int Chl	Sed Chl	Abund	Wet Wt	Org C	Oxy Res
Depth	*	*	*	*	*	*	*	*	*	*	*
Bot Sal	**0.670 <.0001**	*	*	*	*	*	*	*	*	*	*
Bot T	0.162 0.2831	-0.101 0.5008	*	*	*	*	*	*	*	*	*
Bot Sig	**0.593 <.0001**	**0.893 <.0001**	**-0.370 0.0142**	*	*	*	*	*	*	*	*
Bot Chl	-0.276 0.0587	-0.187 0.2160	**0.409 0.0066**	**-0.301 0.0461**	*	*	*	*	*	*	*
Int Chl	**0.336 0.0212**	0.117 0.4382	**0.574 0.0001**	-0.062 0.6832	**0.307 0.0356**	*	*	*	*	*	*
Sed Chl	0.145 0.4039	0.213 0.2272	0.076 0.6657	0.210 0.2353	-0.313 0.0718	0.312 0.0732	*	*	*	*	*
Abund	**-0.596 0.0003**	**-0.329 0.0483**	0.280 0.0933	**-0.350 0.0359**	0.144 0.3820	0.039 0.8111	-0.027 0.8790	*	*	*	*
Wet Wt	**0.583 0.0004**	**0.487 0.0034**	-0.218 0.1910	**0.511 0.0022**	**-0.370 0.0243**	0.247 0.1337	0.125 0.4741	-0.269 0.1020	*	*	*
Org C	**0.569 0.0005**	**0.462 0.0056**	-0.169 0.3103	**0.489 0.0034**	**-0.406 0.0135**	0.190 0.2482	0.142 0.4134	-0.171 0.2988	**0.958 <.0001**	*	*
Oxy Res	0.382 0.0803	0.333 0.1359	-0.400 0.0739	0.333 0.1359	-0.142 0.5144	0.147 0.5003	0.018 0.9386	-0.149 0.4937	0.328 0.1331	0.319 0.1441	*

Spearman's rho → **0.670**

<.0001 ← p-value

Abbreviation	Parameter
Depth	Depth m
Bot Sal	Bottom water salinity ‰
Bot T	Bottom water temperature °C
Bot Sig	Bottom water sigma-t g cm^{-3}
Bot Chl	Bottom water chl-*a* mg m^{-3}
Int Chl	Integrated water column chl-*a* mg m^{-2}
Sed Chl	Sediment chl-*a* mg m^{-2}
Abund	Faunal abundance individuals m^{-2}
Wet Wt	Faunal wet weight g m^{-2}
Org C	Faunal organic carbon biomass g C m^{-2}
Oxy Res	Sediment oxygen respiration mmol O m^{-2} d^{-1}

Appendix E.

Correlation matrix for SLIPP99 data.

	Depth	Bot Sal	Bot T	Bot Sig	Bot Chl	Int Chl	Sed Chl	Abund	Wet Wt	Org C	Oxy Res
Depth	*	*	*	*	*	*	*	*	*	*	*
Bot Sal	**0.682 <.0001**	*	*	*	*	*	*	*	*	*	*
Bot T	**-0.765 <.0001**	**-0.959 <.0001**	*	*	*	*	*	*	*	*	*
Bot Sig	**0.536 0.0064**	**0.977 <.0001**	**-0.963 <.0001**	*	*	*	*	*	*	*	*
Bot Chl	-0.105 0.5527	0.151 0.3936	-0.105 0.5527	0.266 0.1926	*	*	*	*	*	*	*
Int Chl	0.287 0.1046	**0.356 0.0443**	**-0.358 0.0429**	**0.544 0.0077**	**0.831 <.0001**	*	*	*	*	*	*
Sed Chl	0.308 0.0810	**0.497 0.0049**	**-0.449 0.0111**	0.262 0.1991	-0.104 0.5556	-0.072 0.6830	*	*	*	*	*
Abund	**-0.527 0.0033**	**-0.408 0.0230**	**0.488 0.0066**	**-0.403 0.0534**	-0.178 0.3287	-0.315 0.0842	-0.131 0.4743	*	*	*	*
Wet Wt	**0.414 0.0213**	0.258 0.1513	-0.292 0.1037	0.225 0.2796	-0.317 0.0827	-0.116 0.5262	**0.427 0.0192**	**-0.376 0.0363**	*	*	*
Org C	**0.348 0.0528**	0.191 0.2886	-0.242 0.1771	0.148 0.4777	**-0.353 0.0534**	-0.175 0.3389	**0.444 0.0150**	-0.306 0.0880	**0.967 <.0001**	*	*
Oxy Res	**0.629 0.0049**	**0.461 0.0392**	**-0.586 0.0088**	**0.636 0.0174**	0.254 0.2556	0.313 0.1616	-0.059 0.7905	-0.412 0.0803	0.307 0.1927	0.267 0.2579	*

Appendix F.

Correlation matrix for HX177 data.

	Depth	Bot Sal	Bot T	Bot Sig	Bot Chl	Int Chl	Sed Chl	Abund	Wet Wt	Org C	Oxy Res
Depth	-	-	-	*	*	*	*	*	-	-	*
Bot Sal	0.390 0.0001	-	-	*	*	*	*	*	-	-	*
Bot T	0.327 0.0013	0.307 0.0025	-	*	*	*	*	*	*	-	-
Bot Sig	0.290 0.0044	0.952 <.0001	0.136 0.1906	*	*	*	*	*	*	-	-
Bot Chl	-0.408 <.0001	0.114 0.2572	-0.719 <.0001	0.249 0.0159	*	*	*	*	*	-	-
Int Chl	0.308 0.0028	0.102 0.3206	-0.470 <.0001	0.129 0.2104	0.439 <.0001	*	*	*	*	*	-
Sed Chl	-0.029 0.8062	0.510 <.0001	-0.501 <.0001	0.569 <.0001	0.736 <.0001	0.396 0.0008	*	*	*	*	-
Abund	-0.571 <.0001	-0.216 0.0154	0.041 0.7554	-0.232 0.0752	-0.027 0.8356	-0.460 0.0005	-0.243 0.0642	*	*	*	-
Wet Wt	0.167 0.2005	0.257 0.0483	-0.450 0.0002	0.376 0.0039	0.445 0.0006	0.544 <.0001	0.514 <.0001	-0.130 0.3092	*	*	-
Org C	0.142 0.2757	0.256 0.0502	-0.461 0.0004	0.368 0.0047	0.446 0.0006	0.511 <.0001	0.575 <.0001	-0.130 0.3113	0.953 <.0001	*	*
Oxy Res	-0.566 <.0001	0.213 0.1137	-0.329 0.1159	0.002 0.9942	0.533 <.0001	0.048 0.7236	0.556 0.0003	0.321 0.1732	0.430 0.0682	0.393 0.0955	*

Vita

Jaclyn Leigh Clement was born in Jackson, TN on January 19, 1978. She was raised in Huntingdon, TN and attended Huntingdon Grade School and Huntingdon Junior High School. In 1996, she graduated from Huntingdon High School and went on to the University of Tennessee, Knoxville to obtain a B.S. in Biology in 2000 and a M.S. in Ecology and Evolutionary Biology with a concentration in Oceanography in August 2002.