PALEOCLIMATE OF THE LATE OLIGOCENE ARCTIC OCEAN: MOLLUSCAN ISOTOPIC AND BIOTIC EVIDENCE

by

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This thesis was prepared under the direction of the candidate's thesis advisor, Dr. Anton Oleinik, Department of Geosciences, and has been approved by the members of her supervisory committee. It was submitted to the faculty of The Charles E. Schmidt College of Science and was accepted in partial fulfillment of the requirements for the degree of Masters of Science.

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ABSTRACT

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Molluscan isotopic and biotic evidence was used to determine the paleotemperature of the Late Oligocene Arctic Ocean during an important period of climate change. Mollusks were collected from the Nuwok Member type section on the Arctic coast of Alaska. A systematic analysis was conducted to determine the position of Late Oligocene Arctic mollusks within a context of marine Cenozoic evolution and diversification. Oxygen stable isotope ratios of five fossil genera were used to calculate paleotemperatures and analyze growth histories. Taxa were selected to check for compatibility of results between fossil genera from the same environment. Oxygen stable isotope ratios of four recent high-latitude genera were analyzed for comparative purposes. Isotopically derived paleotemperatures represent the first documented quantitative temperatures for the Late Oligocene Arctic Ocean. Isotopic and systematic results give great insight into the extent and degree of Arctic cooling by the Late Oligocene and the origin of modern Arctic mollusks.

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CHAPTER 1

1.0 Introduction

Throughout history, global climate has undergone a significant and complex evolution. Scientists have long endeavored to reconstruct this climatic pathway as well as identify and quantify the agents responsible for this evolution. Reconstructing the Earth's past climate, coupled with an understanding of the forces driving these changes, is the key to comprehending and predicting future climate change.

Knowledge of the Polar Regions, particularly the Arctic, is considered essential for understanding world climate. The Arctic Ocean is an integral part of the world's "weather engine". Climate model studies suggest changes in climate will be felt first and most severely in the Arctic (Manabe and Stouffer, 1994). Changes in Arctic climate are therefore a sensitive indicator of global climate change. Scientists are currently developing methods to predict the future of the Arctic climate. However, the lack of historic climate data is a major obstacle.

Arctic climate has undergone dramatic shifts throughout geologic time. Approximately 70 million years ago, near the end of the Mesozoic Era, the Arctic climate was mild and the Arctic Ocean was ice-free. Studies of the early Cenozoic Arctic climate from Paleocene to Eocene time indicate, although cooler than the end of the Mesozoic, Arctic seas were still much warmer than today (Shackleton, 1984). By the middle of the Cenozoic Era, Late Eocene to Oligocene time, the Arctic climate had begun the dramatic

transition to a much colder, ice-bearing environment commonly associated with modern Arctic settings.

The Eocene-Oligocene transition from a "greenhouse" to a more modern "icehouse" condition is the most significant climatic event of the Cenozoic Era. The Oligocene Epoch is widely regarded as a transition from the Eocene ice-free world to the more modern Miocene world with widespread major ice sheets in the high latitudes. This important period in the Earth's history has been well documented from isotopic and biotic studies of mid-, low- and southern high latitude regions. However, the marine paleoclimate of the Late Oligocene Arctic Ocean has yet to be documented.

Fossil mollusks can be used as qualitative and quantitative paleoclimate indicators. Different mollusk species have different temperature tolerances. Because of these temperature affinities, the biogeographic distribution of molluscan species is directly linked to climatic zones as they are differentiated on the basis of water temperature. Therefore, systematic study of a molluscan fauna can provide significant paleoclimatologic insight. Mollusks can also be used to derive quantitative paleoclimate parameters, such as mean annual and seasonal temperatures, through the use of oxygen stable isotopes present in shell material. This method will be discussed further in Chapter three.

1.1 Objectives

The main purpose of this study is to quantitatively document paleotemperatures of the Late Oligocene Arctic Ocean, based on the stable oxygen isotopes of calcareous mollusk shells. Isotopic composition of congeneric extant species is analyzed for

comparative purposes. Anticipated results include mean annual temperatures as well as seasonal temperature ranges. These results constitute the first detailed quantitative record of absolute temperature values for the Late Oligocene Arctic Ocean.

A secondary purpose of this study is to determine the position of Late Oligocene Arctic mollusks within a context of marine Cenozoic evolution and diversification. A comparative taxonomic analysis of fossil and modern boreal mollusks will help determine the origin and evolutionary history of Late Oligocene Arctic mollusks.

1.2 Hypothesis

Molluscan fossils used in this study are strikingly similar to modern Arctic mollusks. It is hypothesized that the climatic transition to an "icehouse" condition in the Arctic Ocean had occurred much earlier than previously thought and that the late Oligocene Arctic Ocean was almost as cold as it is today. A second hypothesis is that late Oligocene mollusks are the earliest manifestation of modern Arctic Ocean mollusks.

1.3 Relevance of Study

This study will be the first to estimate quantitative paleotemperatures for the Late Oligocene Arctic Ocean. Without calculated temperatures, the Late Oligocene Arctic Ocean cannot be factored into global oceanic circulation models. There is evidence to support the theory that the Arctic Ocean was the sole northern source for at least Oligocene and early Miocene North Atlantic bottom waters (Tucholke and Mountain, 1979; Miller and Tucholke, 1983). If the Arctic was the sole supplier of northern bottom waters to the Atlantic in the late Oligocene, as evidence suggests, relevant data including

paleotemperatures from the Late Oligocene Arctic Ocean are necessary to begin to understand the Arctic role in the production bottom waters. The quantitative data acquired will also help determine how extensive cooling was by the Late Oligocene and potentially demonstrate that the Arctic Ocean had become colder much earlier than previously speculated.

This study will be the first to fill in gaps in data from the global climate record as well as the evolutionary timelines for several groups of Cenozoic mollusks. To date, no such studies have been performed on the Late Oligocene Arctic marine environment. Upon completion, this study is anticipated to contribute invaluable information for climatic modeling as well as for understanding the process of marine evolution in response to dramatic climate change

1.4 Study Area

The study area for this project is located in the Arctic sector of the North Slope at latitude 69°56'49" N and longitude 144°39'55" W (**Figure 1**). The geologic subject of study for this project is the type section of the Nuwok Member of the Sagavanirktok Formation in northeastern Alaska. The type section for the Nuwok Member occurs on the eastern bank of Carter Creek, a stream flowing north into Camden Bay.

1.5 Thesis Organization

The remainder of this thesis is organized into the following chapters: Geologic Setting, Materials and Methods, Isotopic Results and Discussion, Systematics and Conclusions. References are included at the end of the last chapter followed by

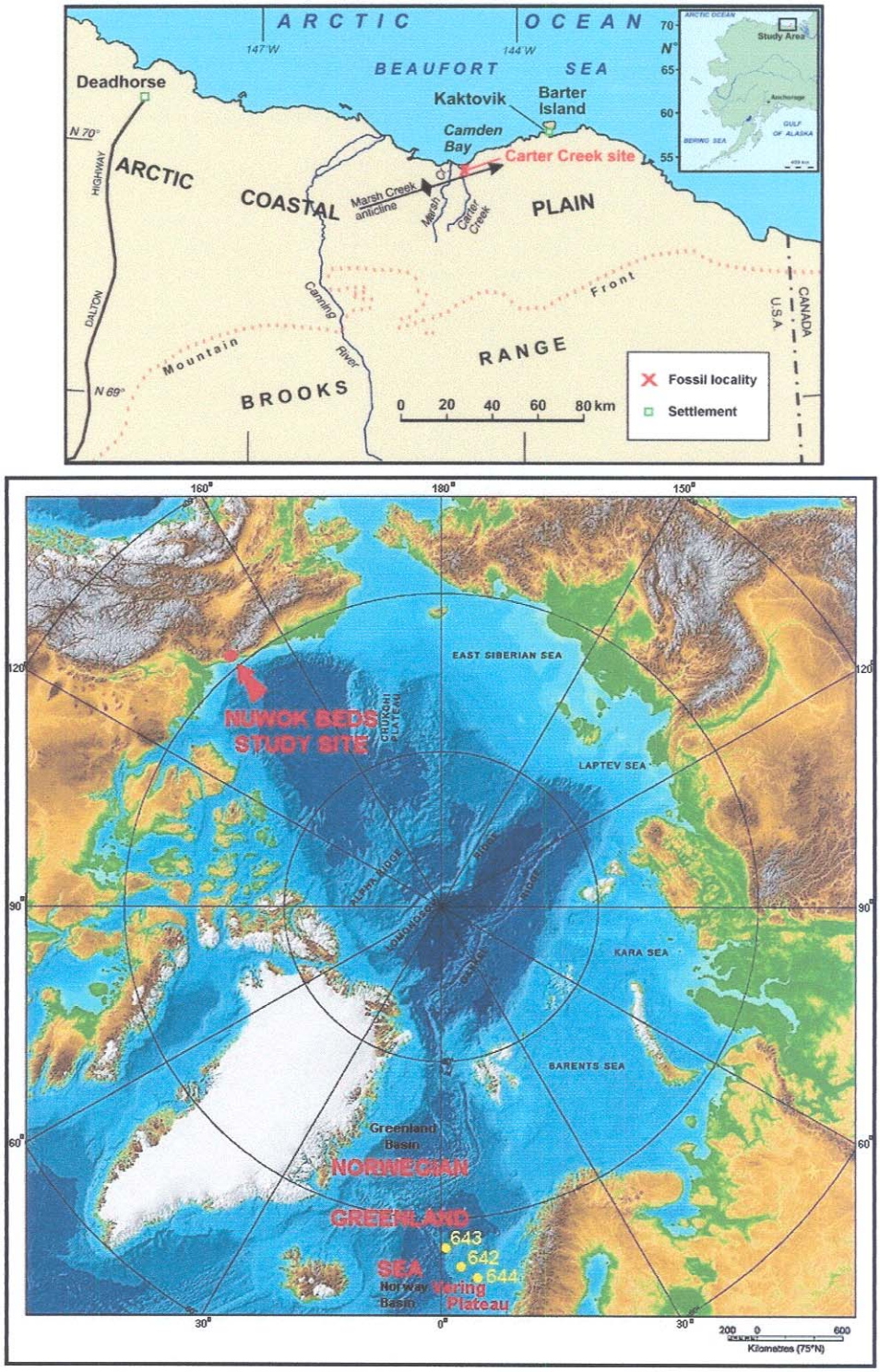

Figure 1. Location of study area at Carter Creek, North Slope, Alaska – The type locality for the Nuwok Member of the Sagavnirktok Formation (Courtesy Oleinik, 2007)

appendices including a systematic index, raw isotope data and temperature and salinity maps.

Chapter 2, Geologic Setting, contains a review of previous geologic studies of the North Slope and Nuwok Member. A detailed stratigraphic section is presented and described. Information regarding the origin of the Nuwok sediments as a cold-seep deposit is also discussed.

Chapter 3, Materials and Methods, describes the theory and methodology of oxygen isotope paleothermometry. The material used in the isotopic and systematic study is briefly reviewed.

Chapter 4, Isotopic Results and Discussion, presents the isotopic measurements from fossil and recent bivalves and associated calculated paleotemperatures. Results are displayed graphically and discussed.

Chapter 5, Systematics, consists of the identifications and descriptions of the Nuwok molluscan fauna. A discussion of the fauna and its environmental, climatic and evolutionary significance follows the taxonomic descriptions.

Chapter 6, Conclusions, discusses the paleoclimate of the Late Oligocene Arctic Ocean as evidenced by the isotopic and systematic analysis conducted during this study.

CHAPTER 2

2.0 Geologic Setting

2.1 Previous Geologic Studies in the North Slope

The earliest documented geologic exploration of the North Slope began in 1816 with the voyages of Kotzebue and Beechey. Kotzebue and Beechey explored the Arctic and subarctic shores of Alaska and recovered abundant Tertiary vertebrate fossils (Richardson, 1854). In 1901, Schrader and Peters of the United States Geological Survey (USGS) described the stratification of supposed Tertiary coastal deposits and collected associated marine invertebrate fossils.

In 1912 Ernest De K. Leffingwell began the first detailed field study of the Canning River region of the North Slope of Alaska. In an attempt to decipher the geologic history of the North Slope, Leffingwell's field activities focused on the collection of fossils and the locating of geologic contacts. Leffingwell's field party was the first to specifically recognize a fossiliferous outcrop along Carter Creek. As a result, the first measured section and description of the outcrop at Carter Creek was published by Leffingwell in 1919. According to Leffingwell, the section at Carter Creek was composed of less than 200 feet of soft shales with a few thin bands of harder, sandy shales dipping 15 to 20 degrees north. He also noted the presence of black chert pebbles and concretions up to a few feet in diameter.

In 1953, as part of the USGS's effort to support US Navy oil exploration, R.H. Morris began a study of the Northern Alaska coastal plain. Coupling field observations with interpretations of photo-geologic material, Morris identified the presence of a twenty mile long east plunging anticline stretching across the Alaskan coastal plain from the Katakturuk River to east of Carter Creek. Morris named the structure the Marsh Creek Anticline and suggested the crest of the Marsh Creek anticline exposed Pliocene beds. At Carter Creek, exposed along the northern limb of the Marsh Creek anticline, Morris reported a sequence of sandstone and shale of approximately 7,266 feet. Only the upper 266 feet were found to contain marine fossils; the lower 7,000 feet were found to contain fossil plant material. Morris' description of the upper 266 feet of exposed beds at Carter Creek closely resembles the description previously published by Leffingwell for less than 200 feet of soft shales at Carter Creek.

Between the years of 1969 to 1972, Detterman, Reiser, Brosge and Dutro (1975) performed a detailed stratigraphic study of northeastern Alaska for the USGS. The use of helicopters and aerial photographs were employed to supplement ground field work. Detterman and others reported an approximately 270 foot sequence starting with a cross-bedded sand unit capped by a pebble conglomerate and followed by a pebbly mudstone and siltstone exposed along Carter Creek . This description and measurement closely resembles those from previous studies, however there was no mention of concretions.

2.2 Previous Studies of the Nuwok Member

Most previous studies involving the beds exposed at Carter Creek were broadly focused on the geology of the North Slope and Arctic coast in general (Leffingwell,

1919; Morris, 1953; Detterman *et al.*, 1975). Prior to this study, the only work solely dedicated to the study of the strata at Carter Creek was conducted by a field party led by Marincovich in 1988. The principal objectives of the 1988 study led by Marincovich were to measure and describe the section and to sample mollusks, foraminifera, ostracodes, and wood fragments in reconnaissance fashion.

Section 2.2 summarizes the observations and conclusions drawn by previous researchers studying the section at Carter Creek. Topics include the designation of the strata as the type section for the Nuwok Member of the Sagavanirktok Formation, paleontologic studies, age determinations, and implications for a cold-seep depositional environment.

2.2.1 Stratigraphy and Nomenclature

Leffingwell made no attempt to formally name or designate a lithostratigraphic rank for the strata he discovered at Carter Creek. The first attempt to name the strata was by Dall during his first review of Leffingwell's fossil collection. Dall gave the name and rank Nuwok Formation for the approximately 200 feet of fossil bearing strata exposed at Carter Creek. However, due to insufficient correlative evidence for such rank designation, the USGS did not formally accept the name. Therefore, some subsequent works referred to the beds at the future Nuwok Member type locality as solely, "the Nuwok", unable to reference lithostratigraphic rank (Dall, 1919, 1920).

Morris' discovery of an additional 7,000 feet of strata exposed at Carter Creek made it possible to correlate the strata with other northeastern Alaska deposits. Morris was the first to suggest correlating the lower, fossil-plant bearing, 7,000 feet of strata at

Carter Creek to the Upper fossil-plant bearing Sagavanirktok Formation of Gryc, Patton and Payne (1951). Gryc, Patton and Payne named the Sagavanirktok Formation to include all Tertiary strata in Northern Alaska. They had described the type section at Franklin Bluffs, located to the west of Carter Creek.

In 1957, F. Stearns MacNeil conducted a paleontological analysis of the fossils collected by Leffingwell and Morris. MacNeil supported the correlation suggested by Morris for the lower 7,000 ft of strata. However, MacNeil proposed the upper 266 ft of marine fossil-bearing strata at Carter Creek be designated a separate formation due to the unlikelihood that the entire Tertiary is represented in a single conformable sequence. The absence of field evidence to support MacNeil's proposition prevented the USGS from formally designating the upper 266 feet at Carter Creek as the Nuwok Formation.

The field and photo-interpretive studies of Dettermen et al. (1975) were the first to supply sufficient evidence to place all of the strata exposed at Carter Creek in a stratigraphic context with the rest of northeastern Alaska. The work of Detterman showed that the upper fossiliferous beds exposed at Carter Creek directly overlie strata that is equivalent to that at Franklin Bluffs, the type section for the Sagavanirktok Formation as designated by Gryc, Patton and Payne (1951).

Detterman et al. (1975) proposed to subdivide the Sagavanirktok Formation into three newly named members (**Figure 2**). Each member was assigned a type section due to the absence of a complete sequence for the Sagavanirktok Formation at any single locality. In ascending order, the new members were entitled the Sagwon Member, the Franklin Bluffs Member and the Nuwok Member. Detterman et al. designated the type section for the Franklin Bluffs Member as what was originally designated by Gryc,

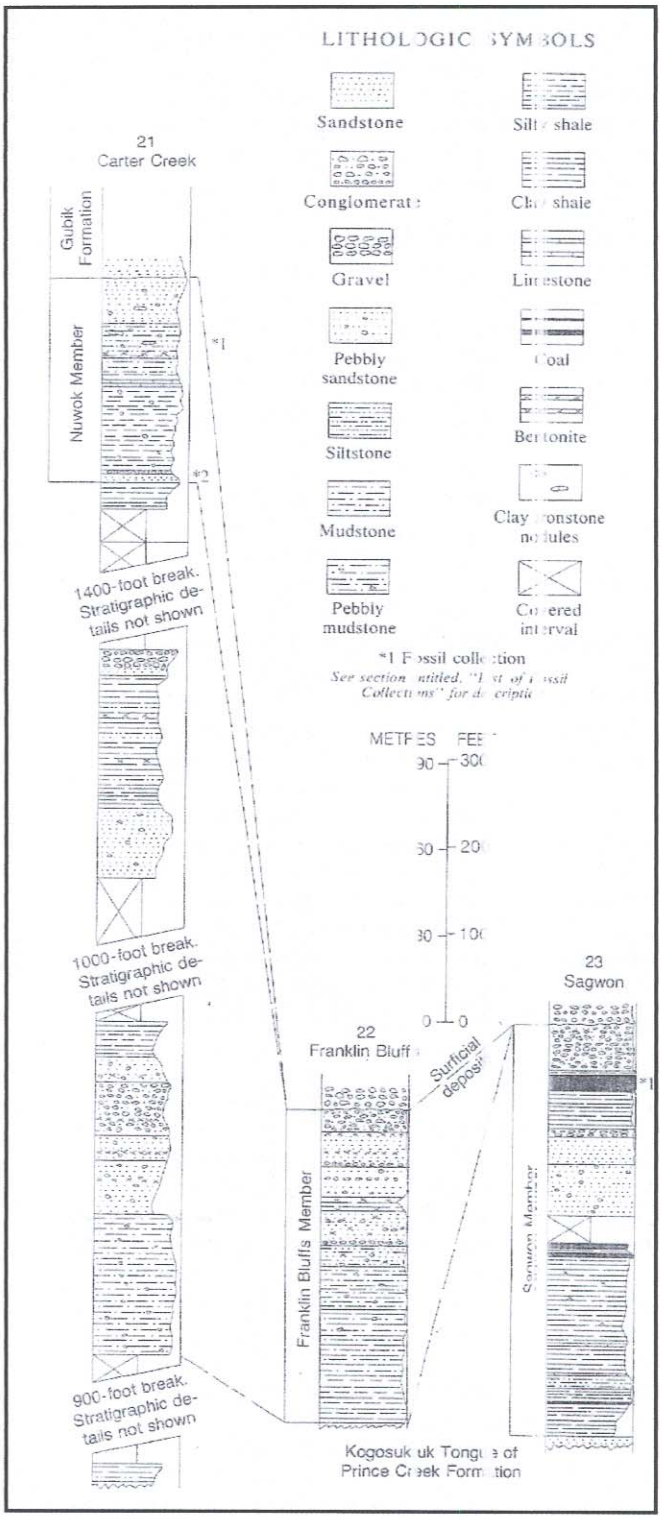

Figure 2. Type sections for members of the Sagavanirktok Formation (After Detterman *et al., 1975)*

Patton and Payne (1951) for the type section of the Sagavanirktok Formation. The lower 7,000 feet of strata exposed along Carter Creek and described by Morris are equivalent to the Franklin Bluffs Member. Detterman et al. designated the type section for the Nuwok Member as the upper 270 feet (80 m) of fossiliferous strata exposed at Carter Creek.

The stratigraphic relationships and associated nomenclature as proposed by Detterman et al. is currently the most widely accepted explanation of Tertiary North Slope stratigraphy. Subsequent studies (McNeil *et al.*, 1982; Young and McNeil, 1984; Marincovich and Brouwers, 1988; McNeil, 1989) at Carter Creek refer to the approximately 270 feet of marine fossil-bearing strata as the Nuwok Member of the Sagavanirktok Formation.

2.2.2 Paleontology

The first collections of macrofossils from Carter Creek were made in 1912 and 1914 by Ernest De K. Leffingwell (1919). These collections include fossil shells and wood. Leffingwell's fossils were identified and described by William H. Dall (1920). Dall (1920) recognized the fossils as unusual for this latitude.

Morris (1953) collected fossil mollusks as well as rock samples from the Nuwok Member. Rock samples collected by Morris were examined by Todd (1957) and two samples were found to contain foraminifera (**Table 1**). Todd described the fauna of foraminifera as "meager…mostly well preserved…and stained reddish brown or occasionally black" (1957, p.223). Todd inferred an Oligocene to Pliocene age for the fauna, however no evidence was found that would favor either a Pacific or Atlantic origin

for the fauna (**Table 2**). Todd also discovered that the two samples contained essentially the same fauna, consisting of 38 species belonging to 24 genera.

MacNeil (1957) reviewed both Leffingwell's collections and Morris' collection of fossil mollusks. Little resemblance was found to Miocene Gulf of Alaska faunas. Under the assumption that the Carter Creek fauna was Late Tertiary in age, MacNeil suggested the Bering Strait was probably closed at this time. MacNeil did recognize a close resemblance to living and fossil Atlantic species belonging to genera such as *Arctica*, *Astarte*, *Chlamys* and *Cyrtodaria*.

The most recent fossil collecting at Carter Creek, prior to this study, was performed by the 1988 field party led by Louie Marincovich of the USGS. Three assemblages of ostracodes and two assemblages of mollusks were identified. Marincovich and Brouwers (1988) noted a lack of affinity with Pacific faunas and a similarity to eastern United States faunas. This judgment concurs with that made by MacNeil (1957).

Marincovich and Brouwers (1988), reported paleontologic correlative evidence for two additional outcrops of the Nuwok Member in northeastern Alaska. Marincovich and Brouwers identified similar mollusks and ostracodes at two locations, Barter Island and Manning point, approximately 45 kilometers east of Carter Creek. Prior to this, no other outcrops of Carter Creek type strata had been reported. The fossils imply that Nuwok strata underlie the coastal plain for at least this distance.

The identifications of benthic foraminifera from Carter Creek were critically revised in the 1980's (McNeil et al., 1982; Young and McNeil, 1984; McNeil, 1989). McNeil and Miller reported the presence of the benthic foraminiferan *Turrilina alsatica*,

[Key: A, abundant; C, common; R, rare]

	Sample 3	Sample 8
Family Tolypammininidae		
Involutina sp. (pl. 28, fig. 1)	R	
Family Lituolidae		
Haplophragmoides? sp. A (pl. 28, fig. 2)	R	
? sp. B	C	
Cyclammina sp. (pl. 28, fig. 3)	R	
Family Miliolidae		
Miliolinella circularis (Bornemann) (pl. 28, fig. 4)	R	C
Family Ophthalmidiidae		
Coruspira sp. (pl. 28, fig. 5)		R
Family Lagenidae		
Robulus cultratus Montfort (pl. 28, fig. 6)	C	R
Marginulina hantkeni Bandy (pl. 28, fig. 7)	R	
Dentalina soluta Reuss (pl. 28, fig. 8)	R	
sp.	R	
Lagena hispidula Cushman (pl. 28, fig. 10)	R	
secata Todd, n. sp. (pl. 28, fig. 12)	C	
semilineata Wright (pl. 28, fig. 9)	R	R
sesquistriata Bagg (pl. 28, fig. 11)		R
Family Polymorphinidae		
Globulina inaequalis Reuss (pl. 28, fig. 13)	C	R
Family Nonionidae		
Nonion eucopis Todd, n. sp. (pl. 28, fig. 15)	A	A
labradoricum (Dawson) (pl. 28, fig. 17)	R	R
Family Buliminidae		
Buliminella curta Cushman (pl. 28, figs. 19, 20)	A	A
Globobulimina affinis (D'Orbigny) (pl. 29, fig. 1)	C	C
Family Buliminidae—Continued		
Bolivina sp. (pl. 29, fig. 2)		R
Angulogerina fluens Todd (pl. 28, figs. 21, 22)	A	A
Ootina apiopleura (Loeblich and Tappan)	R	
borealis Loeblich and Tappan (pl. 29, fig. [illegible])	R	
laevigata D'Orbigny (pl. 29, figs. [illegible])	C	R
lineato-punctata (Heron-Allen and Earland)	R	
squamosa (Montagu) (pl. 29, fig. 3)		R
Fissurina globosa Bornemann (pl. 29, fig. 7)	C	
semimarginata (Reuss) (pl. 29, fig. [illegible])	R	
Family Rotaliidae		
Gyroidina cf. *G. girardana* (Reuss) (pl. 29, fig. 11)	C	C
sp. (pl. 29, fig. 9)	R	
Family Miscellaneidae?		
Elphidiella? brunnescens Todd, n. sp. (pl. 29, fig. 18)	A	A
Family Elphidiidae		
Elphidium discoidale (D'Orbigny) (pl. 28, fig. 14)	C	R
Elphidium? ustulatum Todd, n. sp. (pl. 28, fig. 16)	A	A
Family Cassidulinidae		
Cassidulina cf. *C. subglobosa* Brady (pl. 29, fig. 14)		R
Family Chilostomellidae		
Pullenia salisburyi R. E. and K. C. Stewart (pl. 29, fig. 10)	C	R
Sphaeroidina sp. (pl. 29, fig. 15)	R	
Family Anomalinidae		
Cibicides lobatulus (Walker and Jacob) (pl. 29, fig. 17)	C	
pertucidus Nuttall (pl. 29, figs. 12, 13, 16, 18)	A	A

Table 1. Occurrence and abundance of Formanifera from Carter Creek (After Todd, 1957).

	Ecologic implications				Recorded ranges							
	Shallow	Deep	Cold	Warm	Pre-Tertiary	Paleocene	Eocene	Oligocene	Miocene	Pliocene	Pleistocene	Recent
Abundant:												
Cibicides pertucidus Nuttall							▲	▲	▲			
Angulogerina fluens Todd	×	×	×							?	?	▲
Buliminella curta Cushman	×	×							▲	▲	▲	▲
Common:												
Globobulimina affinis (D'Orbigny)		×							▲	▲	▲	▲
Globulina inaequalis Reuss[1]	?	?					▲	▲	▲	▲	▲	▲
Ootina laevigata D'Orbigny	?	?	×									▲
Fissurina globosa Bornemann								▲				
Pullenia salisburyi R. E. and K. C. Stewart		×					▲	▲	▲	▲	▲	▲
Miliolinella circularis (Bornemann)	×	×						▲	▲	▲	▲	▲
Robulus cultratus Montfort		×						?	▲	▲	?	▲
Elphidium discoidale (D'Orbigny)	×			×				▲	▲	▲	▲	▲
Cibicides lobatulus (Walker and Jacob)[1]	×	×					▲	▲	▲	▲	▲	▲
Rare:												
Nonion labradoricum (Dawson)	×	×	×						▲	▲	▲	▲
Lagena hispidula Cushman		×	×				▲	?	?	▲	▲	▲
semilineata Wright		×	×									▲
Fissurina semimarginata (Reuss)		×								▲	▲	▲
Very rare:												
Dentalina soluta Reuss[1]		×			▲	▲	▲	▲	▲	▲	▲	▲
Marginulina hantkeni Bandy							▲	▲	▲			
Ootina apiopleura (Loeblich and Tappan)	×		×									▲
lineato-punctata (Heron-Allen and Earland)	×		×									▲
squamosa (Montagu)	?	?						▲		▲	▲	▲
borealis Loeblich and Tappan	×		×									▲
Lagena sesquistriata Bagg		×							▲	▲	▲	▲

[1] Cosmopolitan.

Table 2. Stratigraphic ranges and ecologic implications of the already known species of Foraminifera from Carter Creek (After Todd, 1957).

not previously reported by Todd (1957). *T. alsatica* is well documented in Olgicene and uppermost Eocene strata deposited in neritic to bathyal environments (McNeil and Miller, 1990). McNeil and Miller did not report any findings of pre-late Oligocene foraminifera. The implication, with regards to the geologic age of the Nuwok Member, due to the presence of *T. alsatica*, is further discussed in section 2.2.3.ii.

2.2.3 Geologic Age of the Nuwok Member

2.2.3i Relative Age Assignments

The majority of age data for the Nuwok Member has been relatively derived from stratigraphic and biotic studies. Based on taxonomic analysis of Nuwok mollusks and inferred stratigraphic relationships with other North Slope strata, most relative age estimates placed the Nuwok strata in Late Neogene time, either Late Miocene or Pliocene (Dall, 1920; Morris, 1953; MacNeil, 1957; Todd, 1957; Detterman *et al.*, 1975; Marincovich and Brouwers, 1988).

Leffingwell (1919) described the Carter Creek strata as Pliocene in age. Leffingwell's extensive field study of the Coastal Plain to decipher the geologic history of northern Alaska formed the basis for his relative age assignment. Dall (1919) also determined the Carter Creek strata to be Pliocene in age, but on the basis of fossil mollusks.

Morris (1953) reported a fossil-based Late Miocene or Pliocene age for the upper 266 feet of his 7,266 foot section. He reported an Eocene or Oligocene age for the lower 7,000 feet of his section based on the proposed correlation to the similar strata of the

Sagavanirktok Formation, further to the west. Todd (1957) determined an age range from Oligocene to Pliocene, based on her study of fossil benthic foraminifera collected by Morris from Carter Creek (**Table 2**).

MacNeil (1957) and Detterman et al. (1975) both separately assigned a Late Miocene or Pliocene age to the fossiliferous strata at Carter Creek. These assignments were based upon the review of literature discussing fossils previously collected at Carter Creek. Marincovich and Brouwers (1988) assigned a Late Neogene age for the Nuwok Member based on the taxonomic analysis of fossil mollusks and ostracodes collected from the Carter Creek type section.

2.2.3.ii Current Age Data

McNeil and Miller (1990) have provided the most recent and comprehensive attempt to assign an age to the fossiliferous beds at Carter Creek. Two independent methods were employed to produce both isotopically and paleontologically derived age estimates. The age estimates reported by McNeil and Miller differ significantly from that of their predecessors.

McNeil and Miller (1990) are credited with the calculation of the first chemical-based absolute age estimate of the Nuwok Member type section. The ratio of Strontium isotopes ($^{87}Sr/^{86}Sr$) from three samples of foraminifera and one mollusk were measured by McNeil and Miller, and correlated to a standard reference curve previously established from late Eocene to Oligocene strata at a Deep Sea Drilling Project, Site 522. By applying the linear regression for the reference curve, as determined by Miller et al., (1988), to the Strontium isotope ratio values obtained from Carter Creek, McNeil and

Miller obtained an age range from 23.8 to 27.0 Ma, Chattian Age Late Oligocene, for the Nuwok beds (**Table 3**).

Sample Code	$^{87}Sr/^{86}Sr$	Age (Ma)	Stratigraphic Age	Notes
#4	0.708154±18	27.0	Late Oligocene	Benthic forams
#3	0.708195±12	25.8	Late Oligocene	Benthic forams
#2	0.708253±28	24.3	Late Oligocene	Benthic forams
#1	0.708270±0.7	23.8	Late Oligocene	Benthic forams

Table 3. Sr isotope data and age estimates for Nuwok samples adjusted for an NBS-987 value of 0.710253 (After McNeil and Miller, 1990)

During a taxonomic revision of foraminifera from the Nuwok Member at Carter Creek, McNeil and Miller (1990) reported the presence of the Oligocene index *Turrilina alsatica*. Due to the absence of pre-late Oligocene foraminifera, they proposed to narrow the age of the Carter Creek strata to the Late Oligocene.

2.2.4 Glendonite Crystals

2.2.4i Identification

Previous studies have indicated the presence of glendonite crystals in Nuwok strata (Leffingwell, 1919; Morris, 1953; Marincovich and Brouwers, 1988). Leffingwell first noted the "single four-sided crystals tapering from the middle toward each end" and the "clusters of such pointed crystals" "scattered upon the surface of the outcrop" (1919, p.129). Leffingwell did not refer to the crystals as glendonite, although he did indicate they were calcite pseudomorphs after celestite (1919). Morris (1953) found glendonite crystals to be abundant in a 100 foot thick section, 110 feet from the top of the strata he

encountered during his study. Marincovich and Brouwers (1988) observed abundant glendonite crystals in the upper half of an 81 m thick outcrop at Carter Creek.

2.2.4.ii Significance

Glendonite crystals are a rare calcite pseudomorph. Outside of Alaska, the only other well known occurrence of glendonite crystals is in Permian rocks of New South Wales, where they are associated with glaciomarine muds (Suess *et al.*, 1982). Glendonite is the successor of ikaite, which is a metastable carbonate hexahydrate. Ikaite is stable at intermediate depths or at surface pressure only under very low temperatures. At low pressures or high temperatures ikaite decomposes rapidly into a watery, whitish calcite soup (Pauly, 1963; Marland, 1975; Bischoff et al., 1993).

Glendonite in the stratigraphic record is acknowledged to have certain paleoclimatic and paleotemperature implications (David and Taylor, 1905; Boggs, 1972; Kaplan, 1979; Carr et al., 1989; Shearman et al., 1989; Sheard, 1990; Johnston, 1995; De Lurio and Frakes, 1999). Studies in modern settings have shown the glendonite precursor, ikaite, is commonly associated with high alkalinity, near freezing waters, and extant gas hydrates (Greinert *et al.*, 1999). Since the formation of ikaite requires cold water, the presence of an ikaite predecessor, such as glendonite, can be used as a paleoclimate proxy or paleothermometer representing water near freezing conditions. The presence of glendonite crystals in the Nuwok sediments may also indicate the occurrence of ancient gas hydrates during the time of deposition of Nuwok sediments. The precursor mineral, ikaite, may have formed in the presence of hydrocarbons and been replaced by glendonite at the same time of dissociation of paleo-gas hydrates. The

significance of glendonite in relation to the depositional environment of the Nuwok sediments will be discussed further in section 2.5.2.

2.3 Geographic Location of the Study Area

In Alaska, north of the east-west trending Brooks Range, lies the North Slope region. The study area for this project is located in the Arctic sector of the North Slope at latitude 69°56'49" N and longitude 144°39'55" W. Here, the type section of the Nuwok Member is exposed on the northwest side of a hill on the eastern bank of Carter Creek. The hill is located approximately 2.4 km south of Camden Bay of the Beaufort Sea, 45km west of Barter Island, and 160 km east of Prudhoe Bay (**Figure 1**).

The Carter Creek Section is entirely within the boundaries of the Coastal Plain, which lies on the northern edge of the Arctic National Wildlife Refuge. The plain is a broad expanse of nearly featureless tundra and gently rolling hills extending 30 miles south from the Arctic coast. Creeks, streams and rivers, running from the Brooks Range north towards the Beaufort Sea, intersect the plain creating small valleys.

The nearest settlement to the study area is the town of Kaktovik on Barter Island. In July of 2005, Kaktovik was reached by the author and three fellow scientists by plane from Anchorage, Alaska. From Kaktovik, the study area was accessed via a helicopter.

2.4 Geology of the Study Area

The Nuwok Member of the Sagavanirktok Formation, cropping out at the Carter Creek Section, is an Oligocene component of the post-Carboniferous rocks flanking the Brooks Range. It is the uppermost member of the Tertiary Sagavanirktok Formation.

The Sagavanirktok Formation unconformably overlies Upper Cretaceous non-marine sediments, and is unconformably overlain by the unconsolidated surficial deposits of the Pliocene and Pleistocene marine Gubik Formation (Detterman *et al.*, 1975; Magoon, 1994). The Nuwok Member is the only known marine Oligocene deposit anywhere within the Arctic Circle.

North Slope strata exposed at the surface are generally deformed as a result of ongoing orogenic activity. Post-Carboniferous rocks are deformed into northeast-trending folds; Quaternary surficial deposits are uplifted and slightly folded. The intensity of folding decreases away from the Brooks Range (Detterman *et al.*, 1975). Evidence of past deformation is demonstrated by the eastward plunging Marsh Creek anticline stretching across the coastal plain of the North Slope. Pliocene beds are exposed along the crest of the anticline (Morris, 1953). The Oligocene Nuwok Member type section is exposed on the north limb of the Marsh Creek anticline.

2.4.1 Description of the Section at Carter Creek

This section details the geologic observations made by the author during the course of field work in July of 2005. Examination of the Nuwok Member type section at Carter Creek identified approximately 81 m of strata (**Figure 3**), similar to the 80 m previously assigned to the member (Gryc *et al.*, 1951). The section is predominantly composed of thickly bedded, moderately indurated, mudstone interbedded with silty mudstone (**Figure 4**). A limestone bed occurs in the middle of the section, briefly interrupting the mudstone sequence. The limestone exposed at Carter Creek is of particular significance because it is the only Tertiary limestone known in Alaska.

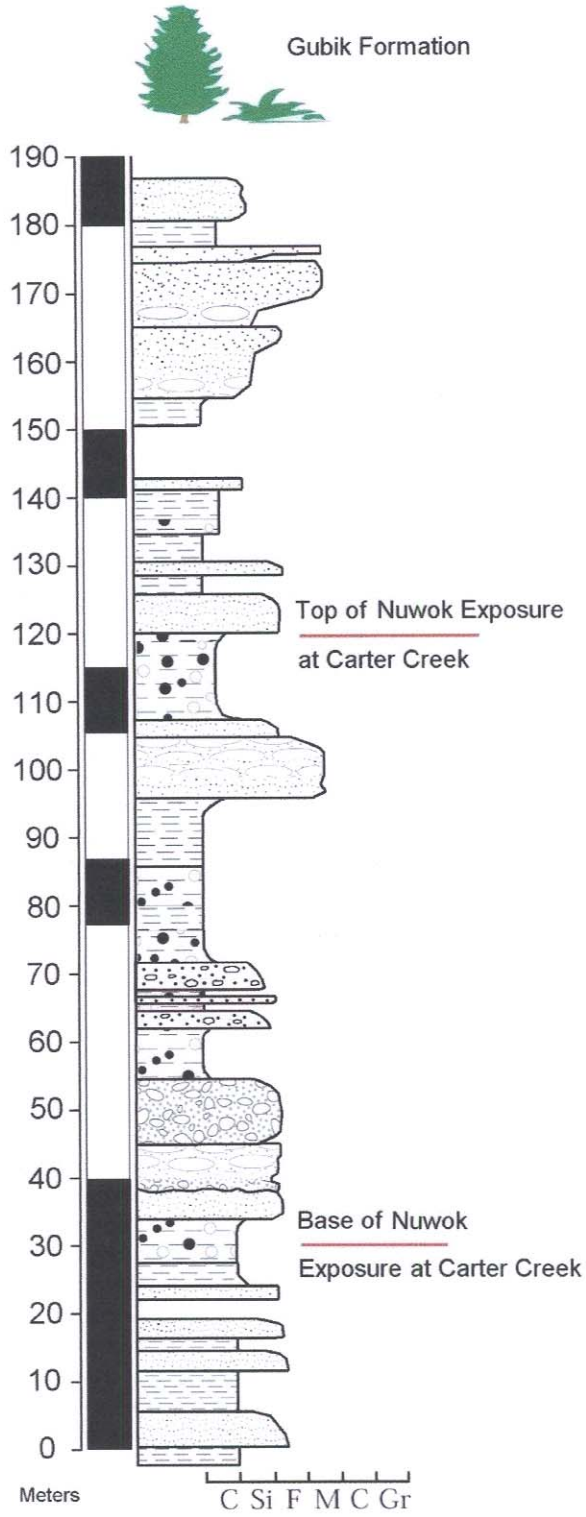

Figure 3. Stratigraphic Section of the Nuwok Member (Modified from a figure courtesy of Oleinik, 2007)

Figure 4. Photographs of approximately 80 meters of the Nuwok Member exposed at Carter Creek, Alaska (Top photo facing southeast and bottom photo facing north by northeast) (Top photo courtesy Oleinik, 2005; Bottom photo Port, 2005)

The strata at Carter Creek are severely weathered. The surface of the outcrop is covered by three to twelve-inches of highly weathered, very loosely consolidated dark brown to gray sandy and clayey silts. Pebbles, gravel, glendonites, some wood and concretions, weathered out from the original material, are scattered about the surface and base of the outcrop.

Bedding planes are scarcely visible on the natural outcrop. However, the manual removal of weathered sediments provided sufficient exposures for basic structural determinations. The structure of the section is uniform, dipping 40° to the northeast. The strata are exposed nearly parallel to the direction of dip.

2.4.1i Lower Nuwok Mudstone

The lower Nuwok strata, from the base to 40 meters up-section, are predominantly dark grey mudstone (**Figure 5**). From approximately 10 to 15 meters from the base of the outcrop the mudstone briefly grades into a lighter grey silty mudstone. Towards the top of the section there is some thin interbedding of dark grey mudstone with lighter grey siltstone.

There are several 15-50 cm thick pebble horizons throughout the section. These layers contain well rounded, black, siliceous, polymict pebbles ranging in size from a few millimeters to over ten centimeters. Lesser amounts of similar pebbles occur scattered throughout the light grey silty mudstone at 10 m up section.

Glendonite crystals were observed to occur in two horizons. The first glendonite horizon occurs at approximately 24 m up section. The second glendonite horizon occurs approximately 35 m up section in a layer of siltstone. Two general crystal forms of

glendonite were observed at the Nuwok outcrop (**Figure 6**). One form consists of a single large, elongate, four-sided crystal with pointed ends. This single crystal is surrounded by multiple smaller similarly shaped crystals which radiate from the base and sides of the central crystal. This form of glendonite from the Nuwok strata was found to exist in a range of lengths, from four centimeters to over thirty centimeters in some instances. The alternative glendonite crystal form consists of similarly sized four-sided crystals all radiating from a central point to form a ball-like cluster. The latter form is typically smaller, with measured clusters ranging from two to eight-centimeters in diameter.

A layer of carbonate concretions occurs approximately 30 m from the base of the outcrop. The concretions are elongate, ranging from 15-25 cm wide and 20-25 cm long. Eroded concretions found on the top of a neighboring hill appear to be pure carbonate. They are dark grey and devoid of fossils.

Three thin horizons, each approximately 10 cm thick, of elongated nodules run through the lower part of the Nuwok section. The horizons are located five, eight and 17 meters up section. The nodules are oval shaped, oriented with their long axis parallel to bedding planes. Nodules are approximately 3 inches long with a yellow exterior ring surrounding an oxidized orange-red center. The nodules are very soft and appear to be siderite with a glauconitic sand core. The highly weathered nodules are fragile and easily fall apart.

Wood fragments are sparse throughout the lower section. The wood has retained its original structure and does not appear to be petrified. Fossil mollusks are common, but are fragile and often crushed in place within the mudstone.

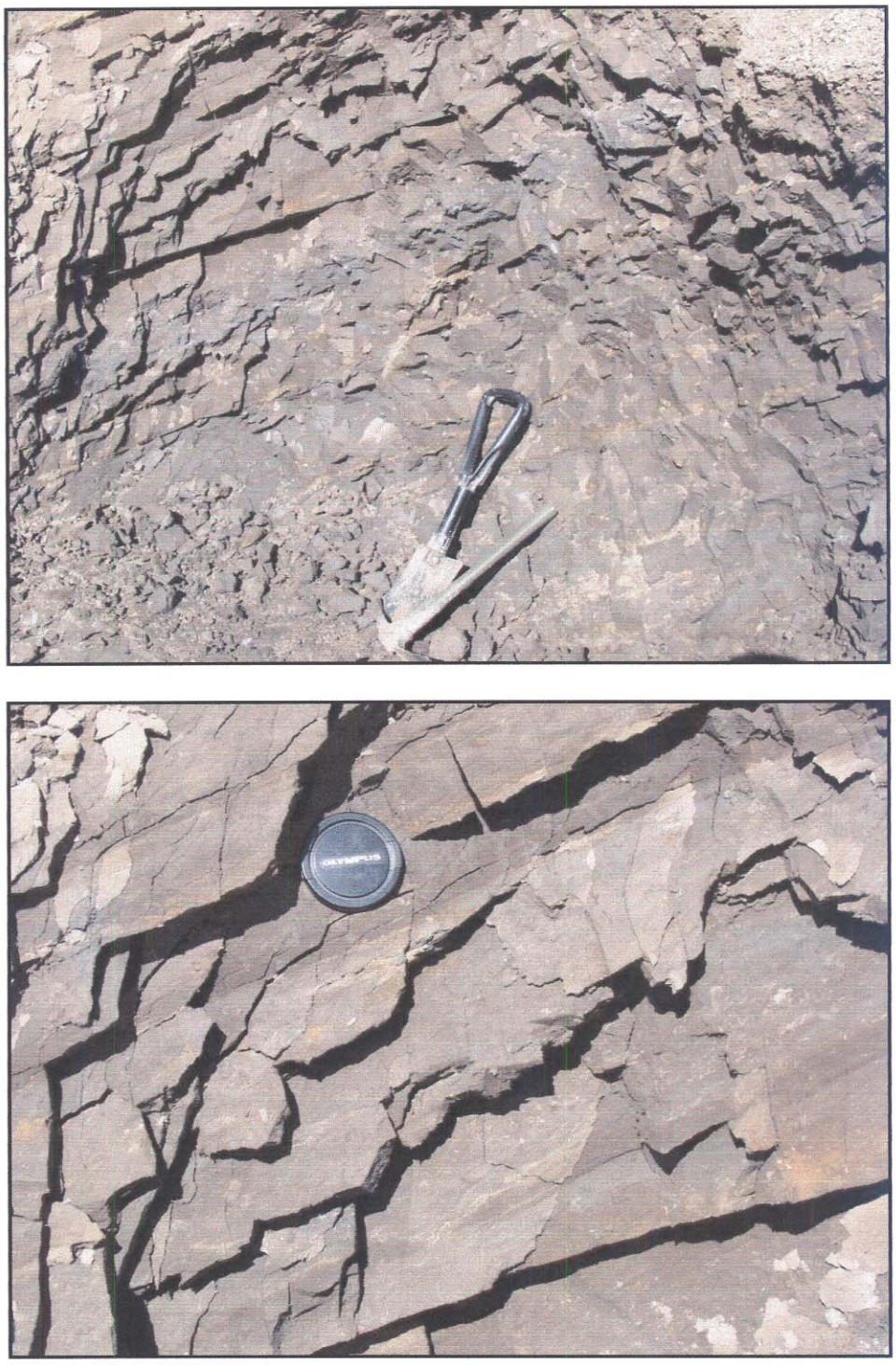

Figure 5. Photographs of mudstone from the Nuwok Member type locality exposure at Carter Creek, Alaska (Top photo Port, 2005; Bottom photo courtesy Oleinik, 2005)

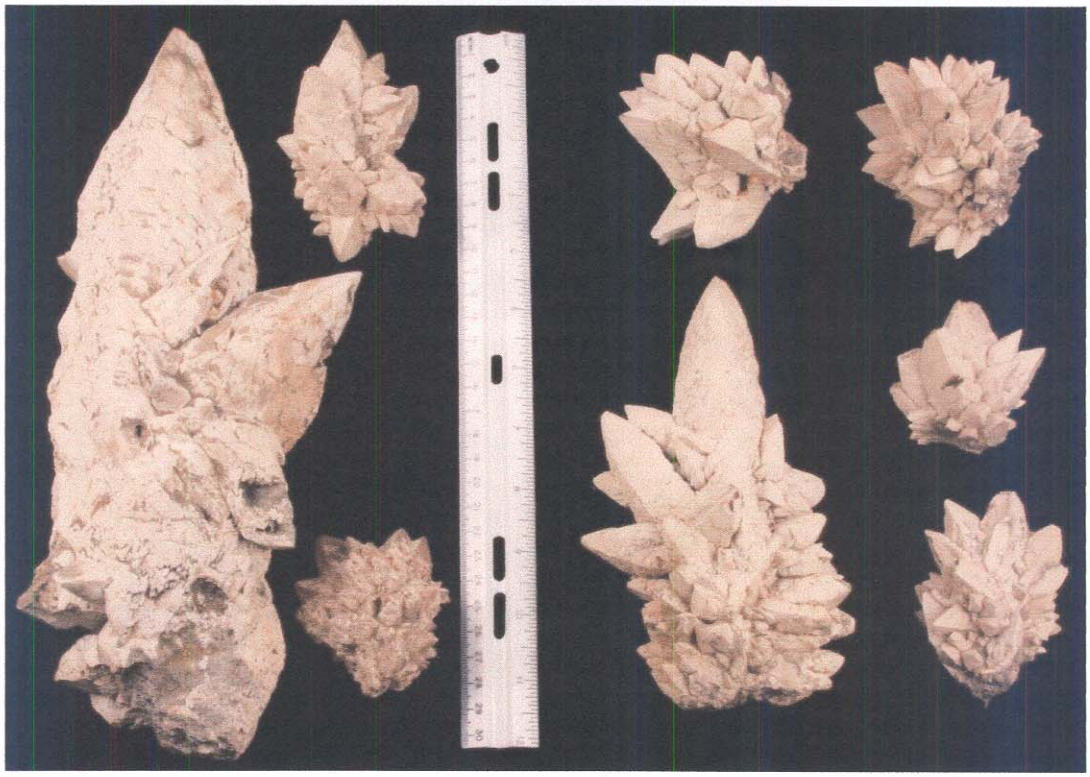

Figure 6. Photographs of glendonite crystals recovered from the Nuwok Member type locality exposure at Carter Creek, Alaska (Courtesy Oleinik, 2005, 2007)

2.4.1ii Middle Nuwok Limestone

A layer of limestone, approximately two to three meters thick, occurs 40 meters from the base of the main outcrop. The oxidized surface of the carbonate deposit is light gray to yellowish-brown. The fresh surface of the rock is dark gray to black. There are abundant, well preserved, both whole and fragmented fossil mollusks. Wood fragments are also abundant with the original wood structure maintained. Non-carbonate impurities in the form of moderately well rounded, smooth pebbles, as well as isolated patches of poorly cemented, iron oxide stained sands, are spread throughout the limestone. Infrequent lenses of coal are also present. The limestone is typically packed with molluscan fossils, wood and pebbles, but there are occasional chunks of pure carbonate material.

Molluscan fossils are more abundant in the limestone than the surrounding mudstone. However, the limestone fauna is less diverse and is dominated by several species not found in the mudstone. The bivalve *Thyasira alaskana* is the most common bivalve in the limestone. A Buccinid gastropod, *Aulacofus sp.*, is one of the most frequently encountered gastropods. No specimens of *T. alaskana* or the gastropod, *Aulacofus sp.,* are found anywhere in Nuwok strata above or below the limestone. The implication, with regards to the origin of the Nuwok sediments, due to the presence of *T. alaskana* and *Aulacofusus sp.*, is further discussed in section 2.5.

2.4.1iii Upper Mudstone Beds

Above the limestone bed, the section continues upward for approximately 40 m. The upper Nuwok is a grey mudstone with abundant pebble horizons as well as scattered

pebbles and also several thin oxidized layers of siderite. The weathered surface shows interbedding of the grey mudstone with silty mudstone. Large wood fragments are found throughout the upper portion of the Nuwok Member. Fossil mollusks and foraminifera are common. Glendonite crystals were not found in the upper Nuwok mudstone beds.

2.5 Origin of Sediments

2.5.1 Modern Hydrocarbon Seep Environments

The majority of hydrocarbons found naturally occur in crude oil where decomposed organic matter provides an abundance of hydrogen and carbon. Hydrocarbons can be gases (e.g. methane and propane), liquids (e.g. hexane and benzene), waxes or low melting solids (e.g. paraffin wax and naphthalene) or polymers (e.g. polyethylene, polypropylene and polystyrene). Gaseous geologic hydrocarbons are referred to as natural gas. Natural gas consists primarily of methane, but also contains significant quantities of ethane, propane, butane and pentane.

Low molecular weight natural gases, like methane, will form hydrates at suitable temperatures and pressures (Kvenvolden, 1993). Methane hydrates are crystalline solids, physically resembling ice, composed mostly of methane and water. The small non-polar methane molecule is trapped inside a cage of hydrogen bonded water molecules. The methane hydrate is not considered a compound because the methane molecule does not bond to the H_2O molecule; it is merely trapped within the H_2O crystal lattice. The formation and dissociation of gas hydrates is a first order phase transition, not a chemical reaction.

These gas hydrates typically form in seafloor sediments where hydrocarbons are seeping out from the Earth's crust. Hydrocarbons and their associated gas hydrate deposits are found in marine sediments of continental slopes and rises at great depths and low temperatures. Gas hydrates can also occur at shallower depths in the cold high-latitude Arctic.

2.5.2 Evidence for Ancient Hydrocarbon Seepage

The limestone strata in the Nuwok Member is the only Tertiary limestone known in Alaska; its origin is therefore of particular interest. Authigenic carbonates of modern marine hydrocarbon seeps are often associated with outcrops of gas hydrates on the sea floor (Aharon, 2000 pers. comm.). There are multiple lines of evidence for a similar hydrocarbon-seep origin for the Nuwok limestone. This limestone is the only known Tertiary cold-seep deposit in the entire Arctic Ocean realm (Campbell *et al.*, 1999).

The first line of evidence to indicate a hydrocarbon-seep origin for the Nuwok limestone is the anomalously light $\delta^{13}C$ signature (to -73 ‰) of the matrix carbonates (micrite, isopachous cements), compatible with a highly ^{13}C-depleted, biogenic methane carbon source (Aharon, 2000 pers. comm.).

Second, a stratigraphically restricted, presumably thiotrophic chemosynthetic fauna (*Solemya*, *Thyasira*) occurs solely in the limestone horizon (Aharon, 2000 pers. comm.). The association of these bivalves is well known in fossil chemosynthetic assemblages (e.g. Campell and Bottjey, 1993, 1995). A Buccinid gastropod, *Aulacofusus*, also occurs in the limestone horizon. Several recent species belonging to the family Buccinidae have been described from modern hydrothermal vents, various

kinds of seeps (Warén & Bouchet, 1993; Okutani et al., 1992, 1993; Okutani & Ohta, 1993) and whale skeletons (Naganuma et al., 1996, 1999).

Lastly, the presence and unique qualities of the glendonite crystals in the Nuwok limestone suggests the preservation of the physical and geochemical imprints of a paleo-gas hydrate (Aharon, 2000 pers. comm.). The presence of glendonite crystals indicates the former presence of the gas hydrate associated ikaite mineral (Greinert et al., 1999). Also, the glendonite crystals are depleted in $\delta^{13}C$ similar to the matrix carbonates (Aahron, Marincovich, 2000, personal communication). Finally, there is an inverse relation between the $\delta^{18}O$ and $\delta^{13}C$ values from the glendonites. This relationship is typical of the environment produced during the dissociation of gas hydrates, and suggests the transition from ikaite to the stable calcite pseudomorph occurred simultaneously with the dissociation of the gas hydrate. Gas hydrates are typically composed of ^{18}O-enriched water and ^{13}C-depleted hydrocarbon gases; upon dissociation of the gas hydrates, pore fluids become enriched in ^{18}O and DIC (dissolved inorganic carbon), with anomalously light $\delta^{13}C$ values (Hesse and Harrison, 1981; Eskikov and Pashkina, 1991; Ussler and Paull, 1995; Ginsburg and Soloviev, 1997; Soloviev and Ginsburg, 1997; Hackworth and Aharon, 2000).

CHAPTER 3

3.0 Materials and Methods

3.1 Oxygen Stable Isotope Geochemistry

Oxygen has three naturally occurring stable isotopes: ^{16}O, ^{17}O and ^{18}O. ^{16}O is the most common oxygen isotope, accounting for approximately 99.76% of atmospheric oxygen. Oxygen has 14 other isotopic states, all of which are unstable and radioactive.

3.1.1 Equilibrium Isotopic Fractionation

Equilibrium isotopic fractionation is the differential concentration of isotopes of an element between the molecules of two substances or two phases of the same substance in chemical equilibrium. This partial separation of isotopes is a result of the thermodynamic properties of the molecules where the isotopes reside. Thermodynamic properties are mass dependant. When a more massive isotope is substituted for a less massive one in a given molecule, the vibrational energy of the molecule is reduced. Therefore, molecules with the same chemical formula, but with different isotopes of an element occupying equivalent positions, will have different energies (Faure, 1986). This leads to higher concentrations of the massive isotopes in substances where the vibrational energy is most sensitive to isotope substitution. An example of equilibrium isotope fractionation is the concentration of heavy isotopes of oxygen in liquid water, relative to

water vapor. The heavier isotope will condense more readily than the lighter isotope, and the lighter isotope will evaporate more readily than the heavier.

Harold C. Urey (1947) was the first to suggest that temperature controls the degree of isotopic fractionation during physical processes, such as in the condensation and evaporation of H_2O as described above. Low temperatures produce the highest degree of fractionation, while at very high temperatures virtually no fractionation will occur. A fraction factor (α) can be calculated to represent the degree of fractionation by:

Eq. 1 $\alpha = [({}^1x/{}^2x)_{phase\ 1}/({}^1x/{}^2x)_{phase\ 2}]$

,where ${}^1\mathbf{x}$ and ${}^2\mathbf{x}$ are isotopes of an element; α will approach 1 as temperature increases.

Urey (1947) also suggested that oxygen isotope fractionation occurs between calcium carbonate ($CaCO_3$) and the oceanic waters in which it is deposited, and that the extent of this fractionation varies with temperature. This idea forms the basis for the oxygen isotope method of determining paleotemperatures.

3.1.2 Oxygen Isotope Paleothermometry and Mollusks

Urey (1947) pioneered the study which demonstrated the correlation between the ratio of heavy to light oxygen isotopes in deposited material and the temperature at the time of deposition. Urey (1947) postulated that the determination of temperatures of ancient oceans should be possible, in principle, by measuring the ${}^{18}O$ content of fossil shells. The following section describes the principles and methodologies behind the use

of oxygen isotope measurements from fossil carbonate shell material as a proxy for paleotemperatures.

3.1.3 Carbonate-Water Isotopic Temperature Scale

Mollusks secrete a calcium carbonate shell as they grow. Studies of modern mollusks have shown that the isotopic composition of the shell material is in near-isotopic equilibrium with the ambient waters in which the organism is growing. At isotopic equilibrium, the forward and backward isotopic exchange reaction rates between two substances are identical. The isotopic exchange reaction for calcium carbonate and water is written as:

Eq. 2 $$\tfrac{1}{3}CaC^{16}O_3 + H_2{}^{18}O \leftrightarrow \tfrac{1}{3}CaC^{18}O_3 + H_2{}^{16}O$$

The difference between isotopic ratios of each substance will remain constant at a given temperature if the calcium carbonate is precipitated in equilibrium with the water. This "difference" is called a fraction factor (α). The fractionation factor (α) for the oxygen isotopic exchange between calcium carbonate and water is 1.0286 at 25°C (O'neil & Clayton, 1964). Calcite is therefore enriched in ^{18}O relative to water at equilibrium temperature.

It has been shown that isotopic changes are recorded instantly by living organisms in the oceans (Epstein et al., 1953). This indicates that, as long as a fossil shell has been assigned an accurate age, paleotemperature reconstructions can be assumed to describe

the water at the time the organism was living. In other words, equilibration time of living carbonate secreting organisms is negligible.

Several paleotemperature equations based on oxygen isotope ratios from carbonate and water have been published and modified since the pioneering work of Urey in 1947. McRea (1950) published the first paleotemperature equation derived from inorganic calcite. Epstein et al. (1951, 1953) were the first to establish an equation using organically precipitated carbonates. Epstein et al. (1951, 1953) empirically determined the relationship between the $^{18}O/^{16}O$ ratio in mollusk shells secreted in equilibrium with ambient waters and temperature by analyzing a series of samples from shells that had either grown in temperature-controlled aquaria or been collected at natural sites where the temperature had been carefully monitored. This equation as modified by Craig (1965) is:

Eq. 3 $$T(°C) = 16.9 - 4.2\,(\delta^{18}O_{carbonate} - \delta^{18}O_{water}) + 0.13\,(\delta^{18}O_{carbonate} - \delta^{18}O_{water})^2$$

The equation has been most recently modified by Grossman and Ku (1986) to suit organically precipitated marine aragonite. Grossman and Ku (1986) produced evidence that oxygen isotope fractionation between aragonite and water differs from that between calcite and water, and have modified the equation as follows:

Eq. 4 $$T(°C) = 20.6 - 4.34\,(\delta^{18}O_{aragonite} - \delta^{18}O_{water})$$

The $\delta^{18}O$ value of the carbonate is an expression of the measured oxygen isotope ratios, and will be described in the following section. The $\delta^{18}O$ of the water is an

estimated value of the oxygen isotope ratio for the ambient water in which the carbonate has been precipitated. Special care must be taken when determining the $\delta^{18}O$ value to use for ancient waters.

3.1.4 Measuring and Reporting Oxygen Isotope Values

Oxygen isotope compositions are reported as δ (delta) values in parts per thousand (‰) relative to an international reference standard of known composition. International standards are necessary for laboratories to ensure equipment used to measure isotopes is calibrated. δ values for oxygen isotopes are calculated by:

Eq. 5 $$\delta^{18}O_{sample} \text{ (in ‰)} = ([(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard}] - 1) \cdot 10^3$$

A positive δ value means the isotopic ratio of the sample is higher than that of the standard, and a negative δ value means the isotopic ratio of the sample is lower than that of the standard.

$\delta^{18}O$ values for naturally occurring waters are reported relative to the Vienna Standard Mean Ocean Water (VSMOW) standard (Craig, 1961). $\delta\ ^{18}O$ values for low-temperature carbonates are reported to the Vienna Pee Dee Belemnite (VPDB) standard (Urey et al., 1951). A sample and a known international reference standard are typically analyzed simultaneously to ensure the measuring is properly calibrated. Small quantities of these reference standards are available for calibration purposes from both the National Institute of Standards and Technology (NIST) in the USA and the International Atomic Energy Agency (IAEA) in Vienna. In order to compare $\delta^{18}O$ values from samples

referenced to different standards, such as ocean water (VSMOW) and a carbonate (VPDB), the following conversion must be applied:

Eq. 6 $$\delta^{18}O_{VSMOW} = 1.03086\ \delta^{18}O_{VPBD} + 30.86\ ‰$$

Oxygen isotopic ratios are measured by a mass spectrometer. Mass spectrometers analyze samples in gas form; the oxygen in the carbonate sample must be converted into a gas (Mcrea, 1950). Oxygen isotopes are analyzed as CO_2. A powdered sample of calcium carbonate reacted with orthophosphoric acid will produce carbon dioxide, calcium hydrogen phosphate and water according to the reaction:

Eq. 7 $$CaCO_3 + H_3PO_4 \leftrightarrow CaHPO_4 + CO_2 + H_2O$$

The gas is introduced into the mass spectrometer through a small gas leak. The gas is ionized by electron bombardment producing CO_2^+ ions. The ions pass through a magnetic field where they are deflected. Heavy and light isotopes are deflected along different paths. Collector cups for each mass (^{16}O and ^{18}O) are placed at the appropriate position next to the magnet where the charge delivered by the ions may be measured. The charge measured by each collector cup is proportional to the number of ions of each mass.

3.1.5 $\delta^{18}O$ Variability of Marine Waters

In order to accurately determine the temperature of ancient oceans using oxygen isotopes, both the $\delta^{18}O$ values of the fossil carbonate and the ambient water where deposition occurred must be known. Since there is no way to directly measure the $\delta^{18}O$ of ancient waters, this value must be inferred. When inferring the isotopic composition of ancient seawater it must be taken into account that the $\delta^{18}O$ of seawater varies spatially and temporally. This is because the oxygen isotope composition of seawater is affected by global ice volume, local changes in salinity and changes in ocean circulation.

During global periods of extensive ice formation, oceans experience a large net evaporative loss (Saltzman, 2002). The lighter isotope, ^{16}O, more readily evaporates resulting in residual ocean water enriched with the heavier isotope, ^{18}O (Saltzman, 2002). If accumulation of global ice volume continues, the amount of global ^{16}O locked up in polar ice caps and glaciers will also continue to increase, further enhancing the isotopically heavy condition of contemporaneous seawater. During periods of reduction in global ice volume, isotopically light meltwaters are released into oceans lowering the $\delta^{18}O$ of seawater.

3.1.6 Fossil Carbonate Diagenesis

The original isotopic ratio of fossil carbonate material must be measured if they are to be used to calculate accurate paleotemperatures. Isotopic ratios may be altered or replaced during certain physiochemical diagenetic processes such as solution, recrystallization, replacement, cementation, and authigenesis (Marshall, 1992). The isotopic composition of a shell will be preserved until it dissolves and recrystallizes

during diagenesis (Hoeffs, 1997). Therefore, the most suitable shells for analysis are those with the best geochemical and physical preservation.

If the original carbonate mineralogy has been preserved it is likely that the original isotopic ratio is also preserved. Aragonite and high-magnesium calcite are metastable minerals. Fossils originally precipitated as aragonite will readily convert to calcite during diagenesis, and must be examined to determine if the original aragonite is still present. Fossils originally precipitated as low-magnesium calcite have the least potential for diagenetic alteration of original chemistry.

3.2 Field and Museum Collections

The molluscan fossils used in the isotopic and systematic study were collected by the author on the North Slope of Alaska. The fossils were collected from the type locality outcrop of the Nuwok Member of the Sagavanirktok Formation. This outcrop is located approximately one and a half miles south of the Arctic Coast, along Carter Creek. Collecting took place during the summer of 2005 by Oleinik and Marincovich and assisted by the author and a fellow graduate student. 262 specimens were used for the systematic study of the fauna. Five species from five genera were used for the isotopic study. Six individuals were selected for analysis. Species and individual specimens deemed the most suitable for isotopic evaluation were selected from the Nuwok molluscan fauna. The history of successful determination of isotopically derived paleotemperatures for each species and the preservation of individual specimens were reviewed prior to selection.

The recent bivalves used for the isotopic study were obtained from the California Academy of Sciences, Department of Invertebrate Zoology and Geology collections. Four recent bivalve species from four genera were analyzed for the isotopic study. Recent bivalves were selected based on the closest extant congeneric (conspecific if possible) relatives of the fossil species. Specimens were collected from high latitude cold water environments similar to the paleoenvironment represented by the Nuwok deposits.

3.3 Sampling Techniques and Sample Preparation

Fossil shells were cleaned from a hard carbonate matrix using a pressurized air drill. Shells were then examined under a microscope where remaining sediments were removed with dental picks and small brushes. In order to remove any remaining organic matter, all shells were soaked in a 30% hydrogen peroxide solution followed by a thorough rinse with de-ionized water. All shells were given ample time to dry completely prior to sampling.

Recent specimens were soaked in bleach for approximately 12 hours to remove organic matter. They were then rinsed with de-ionized water and allowed to dry. Prior to sampling, recent bivalves were soaked in 30% hydrogen peroxide solution followed by a rinse with de-ionized water. Shells were allowed to dry thoroughly before sampling.

Thicker shells (*Arctica, Thyasira* and *Macoma*) were sampled by the author using a hand operated drill in the laboratory at Florida Atlantic University. Smaller and thinner shells (*Astarte* and *Cyrtodaria*) were sampled by Dr. Anton Oleinik using a Leica New Wave digital micromill with a computer-controlled three dimensional stage, located at the University of Miami. Prior to micromill sampling, specimens were prepared by the author

by cutting parallel to the maximum growth axis with a ¾ inch double-sided diamond disc bit on a hand operated drill. They were then polished on the cut side, mounted on glass and cut and polished on the opposite side.

Specimens were milled using a 0.5 mm carbide bit to collect samples at 0.42 to 1.65 mm intervals from the outer shell surface along a transect of the maximum growth axis, across the growth bands from the umbo area to ventral margin. For the micromill sampling, growth bands were digitized and sampling passes parallel to growth lines were calculated. Hand samples were taken as 0.2 to 0.4 mm deep and 1.6 to 10 mm long grooves along the same growth band to account for potential isotopic variability within growth bands. Powdered samples did not exceed 25 μg for the micromilled specimens and 50 μg for the hand milled specimens. Powder samples were analyzed for stable oxygen and carbon using a Kiel II attached to a Finnigan Delta-plus mass spectrometer at the Stable Isotope Laboratory, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami.

3.4 Paleotemperature Calculation

Oxygen and carbon isotopic results are reported relative to the PDB (VPDB) (NBS-19) standard. Temperatures were calculated using the equation modified by Grossman and Ku (1986) (Eq. 3) for biogenically precipitated aragonite. The $\delta^{18}O$ value for Oligocene Arctic waters was estimated to be -1.3‰ using data supplied by Lear et al. (2000) with a correction for high latitudes, as determined by Zachos et al. (1994). The oxygen isotopic composition of ambient water for recent taxa was taken from the global seawater $\delta^{18}O$ database (Schmidt, Bigg, Rohling, 1999, Bigg & Rohling, 2000), and

selected based on the locality. The mean standard deviations for the cumulative of 300 samples milled from both recent and fossil specimens were 0.40‰ for $\delta^{18}O$ and 0.67‰ for $\delta^{13}C$. Analytical precision for all samples was better than ±0.07‰ for $\delta^{18}O$ and ± 0.03‰ for $\delta^{13}C$.

3.5 Isotopic Study of Target Genera

Thyasira

The genus *Thyasira* has been recorded as far back as the Cretaceous (Coan et al., 2000). *Thyasira* is well represented in cold waters and is often associated with modern and ancient cold-seep environments. Chemosynthetic *Thyasira* reside in low-oxygen environments with free hydrogen sulfide (Coan et al., 2006; Campbell and Bottjer, 1993, 1995). Although *Thyasira* has very fine, irregular growth lines, the genus was selected for isotopic analysis because of the abundance of well preserved, seemingly unaltered specimens of a sufficient size.

Astarte

The genus *Astarte* is recorded as early as the Jurassic. Today *Astarte* is predominantly circumboreal, however a variety of extinct forms are known from warm and subtropical regions (Coan et al., 2000). Although *Astarte* is rather small for isotopic analysis, the Nuwok *Astarte* is incredibly well preserved and growth lines are clearly visible.

Macoma

The genus *Macoma* dates back to Eocene time and is well documented in modern Arctic and circumboreal waters (Coan et al., 2000). *Macoma* were also well preserved in the Nuwok sediments.

Arctica

The genus *Arctica* is composed of one living species, *Arctica islandica*. *A. islandica* has a northernmost limit of central Norway and northern Iceland (Marincovich et al., 1990). Numerous fossils species of *Arctica* have been described. *Arctica* is an optimal choice for isotopic analysis. *Arctica* are large, long lived bivalves. Nuwok *Arctica* were moderately well preserved, extra care was taken to select the most suitable specimen.

Cyrtodaria

The genus *Cyrtodaria* is recorded as far back as the Paleocene. It is typical of Arctic fauna and has also been documented in the Bering Sea (Coan et al., 2000). Nuwok *Cyrtodaria* are incredibly well preserved mineralogically, although many shells had been broken in place within the sediments.

CHAPTER 4

4.0 Isotopic Results and Discussion

4.1 Isotopic Profiles and Calculated Water Temperatures

Results of the stable isotope analysis and the corresponding calculated water temperature for each of the recent and fossil specimens of the five genera analyzed are presented in the following section. Isotopic profiles and temperature determinations, including $\delta^{18}O$ seawater values are discussed for each specimen. The results are discussed and displayed visually; sample number one corresponds to the bivalve umbo (first growth), and the last sample corresponds to the ventral margin (last growth).

4.1.1 *Thyasira alaskana* (Oligocene)

The fossil specimen of *Thyasira alaskana* was collected from the limestone layer approximately 40m from the base of the main outcrop at Carter Creek. The specimen was sampled 19 times along the maximum growth axis of 31.3 mm from the dorsal to the ventral margin of the shell. The average sample interval was 1.65 mm.

The isotopic profile shows distinct intra-shell cyclicity in $\delta^{18}O$, and to a lesser extent in $\delta^{13}C$ (**Figure 7**). There is a slight positive correlation between the $\delta^{18}O$ and $\delta^{13}C$ values. The profile appears to represent four and a half growth cycles. Growth bands are not easily distinguishable on the shell. The oxygen isotope profile displays a nearly symmetrical saw tooth pattern with nearly equal heavy and light $\delta^{18}O$ excursions,

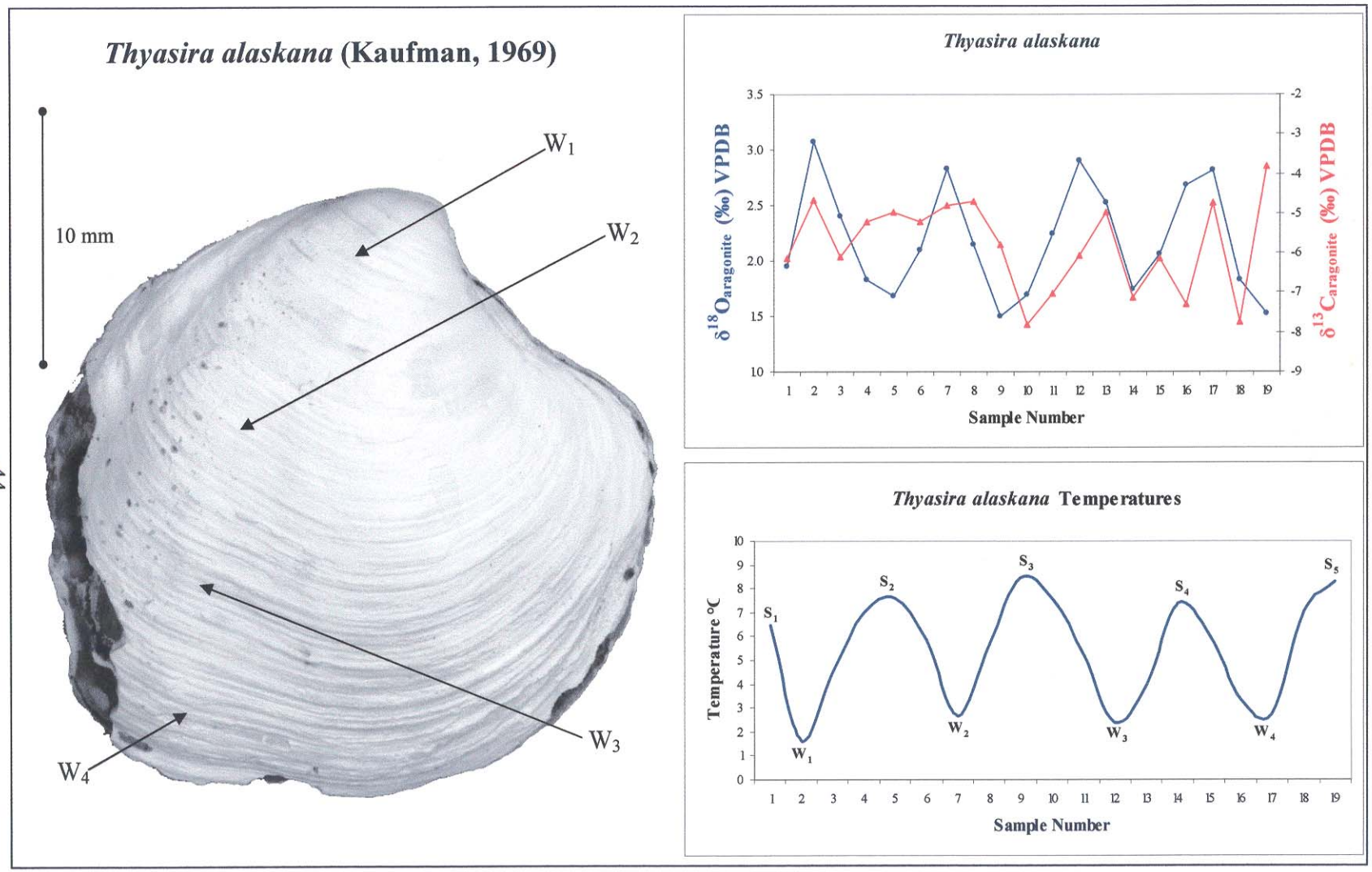

Figure 7. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a fossil specimen of *Thyasira alaskana* collected from the Nuwok Member type locality at Carter Creek, Alaska.

suggesting continuous growth at a steady rate. $\delta^{18}O$ values are relatively enriched throughout the shell transects with values ranging from 1.50‰ to 3.07‰, with an average of 2.19‰.

Ambient water temperatures were calculated using a $\delta^{18}O_{water}$ value of -1.3‰. Calculated paleotemperatures ranged from 1.6342°C to 8.456219°C, with an average of 5.46838°C.

4.1.2 *Thyasira trisinuata* (Recent)

The recent specimen of *T. trisinuata* was collected from off the coast of Seattle, Washington. The specimen was sampled 81 times along the maximum growth axis of 48.7 mm from the dorsal to the ventral margin of the shell. The average sample interval was 0.60 mm.

The isotopic profile shows distinct intra-shell cyclicity in $\delta^{18}O$ values, representing nine cycles of growth (**Figure 8**). The $\delta^{13}C$ profile does show some cyclicity, but with an overall increasing trend. There is a sharp isotopically light $\delta^{13}C$ excursion from sample 50 to 52. Sharp peaks of lighter $\delta^{18}O$ values indicate a slow-down or temporary cessation of growth during the cold season. The fourth isotopically light excursions from sample 28 to 31 is particularly pronounced. $\delta^{18}O$ values are relatively depeleted, with values ranging from -1.87‰ to 0.80‰, with an average of 0.22‰. Ambient water temperatures were calculated using a $\delta^{18}O$water value of -2.5‰. Calculated temperatures ranged from 6.29°C to 17.85°C, with an average of 8.79°C.

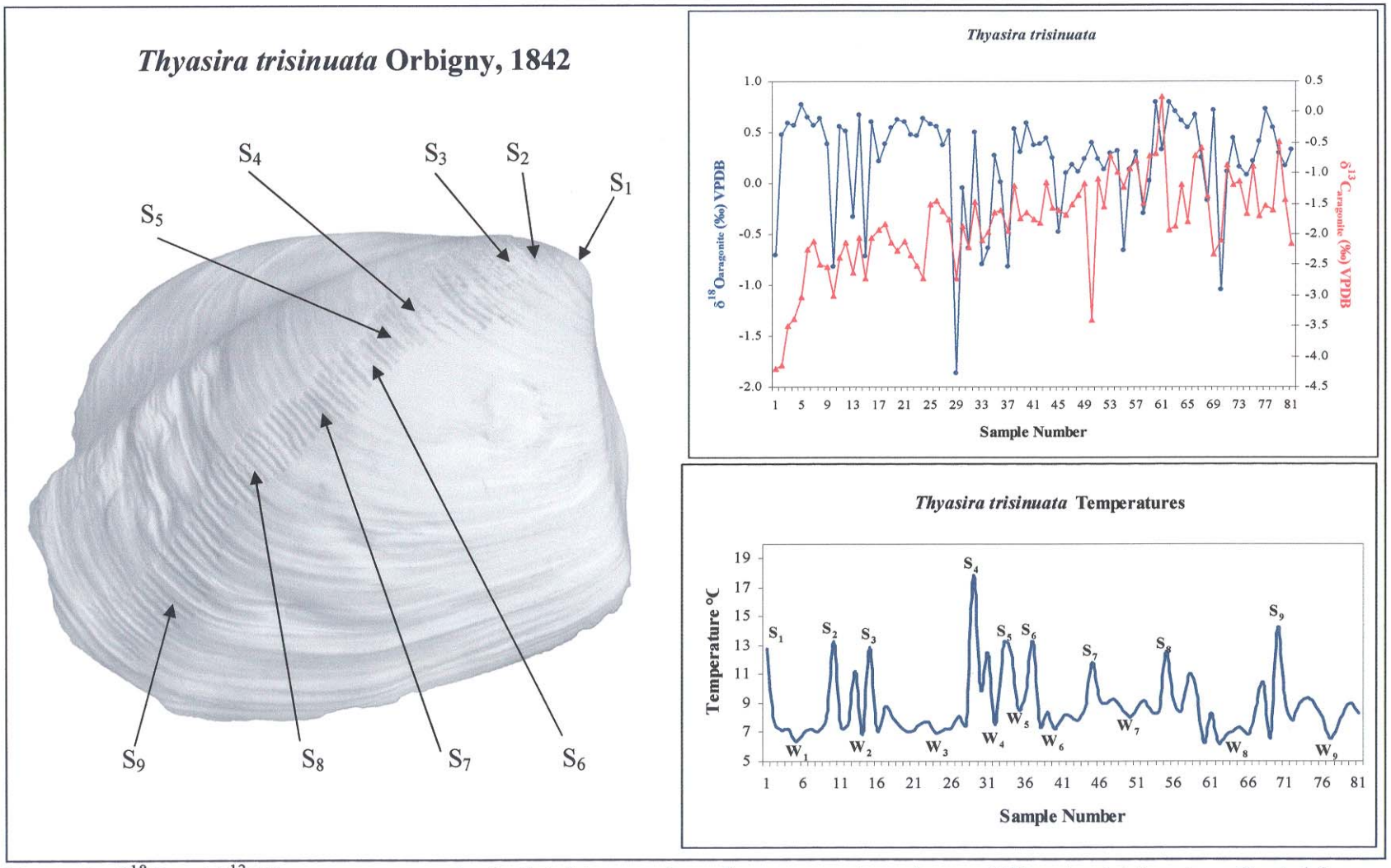

Figure 8. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a recent specimen of *Thyasira trisinuata* collected from off the coast of Seattle, Washington.

4.1.3 *Astarte martini* (Oligocene)

Two fossil specimens of *Astarte martini* were analyzed. Both shells were collected from mudstone beds approximately 53m from the base of the main outcrop at Carter Creek.

The first specimen was sampled by hand. The specimen was sampled 27 times along the maximum growth axis of 15.43 mm from the dorsal to the ventral margin. The average sample interval was 0.57 mm.

The isotopic profile shows distinct records of seasonality representing six and a half growth cycles (**Figure 9**). The $\delta^{18}O$ and $\delta^{13}C$ values appear to have a negative relationship. $\delta^{18}O$ values display as an assymetrical saw tooth pattern with one particularly distinct isotopically heavy excursion during the winter of the fourth growth cycle. $\delta^{18}O$ heavy and light peaks are nearly equally spaced, suggesting continous and rapid growth. Growth bands are easily distinguished on this shell. $\delta^{18}O$ values range from 1.31‰ to 3.07‰, with an average of 2.04‰. Ambient water temperatures were calculated using a $\delta^{18}O_{water}$ value of -1.3‰. Calculated paleotemperatures range from 1.6342°C to 9.2726°C, with an average of 6.0963°C.

The second specimen was sampled by micromill. The shell was sampled 33 times along the maximum growth axis of 15.76 mm from the dorsal to the ventral margin. The average sample interval was 0.48 mm.

The resulting oxygen isotope data displays an assymetrical saw tooth pattern trending towards increased heavy isotope concentrations (**Figure 10**). The isotopic profile represents seven years of growth. The first five cycles are displayed by sharp isotopically light peaks, while the last two cycles of growth are represented by broad and

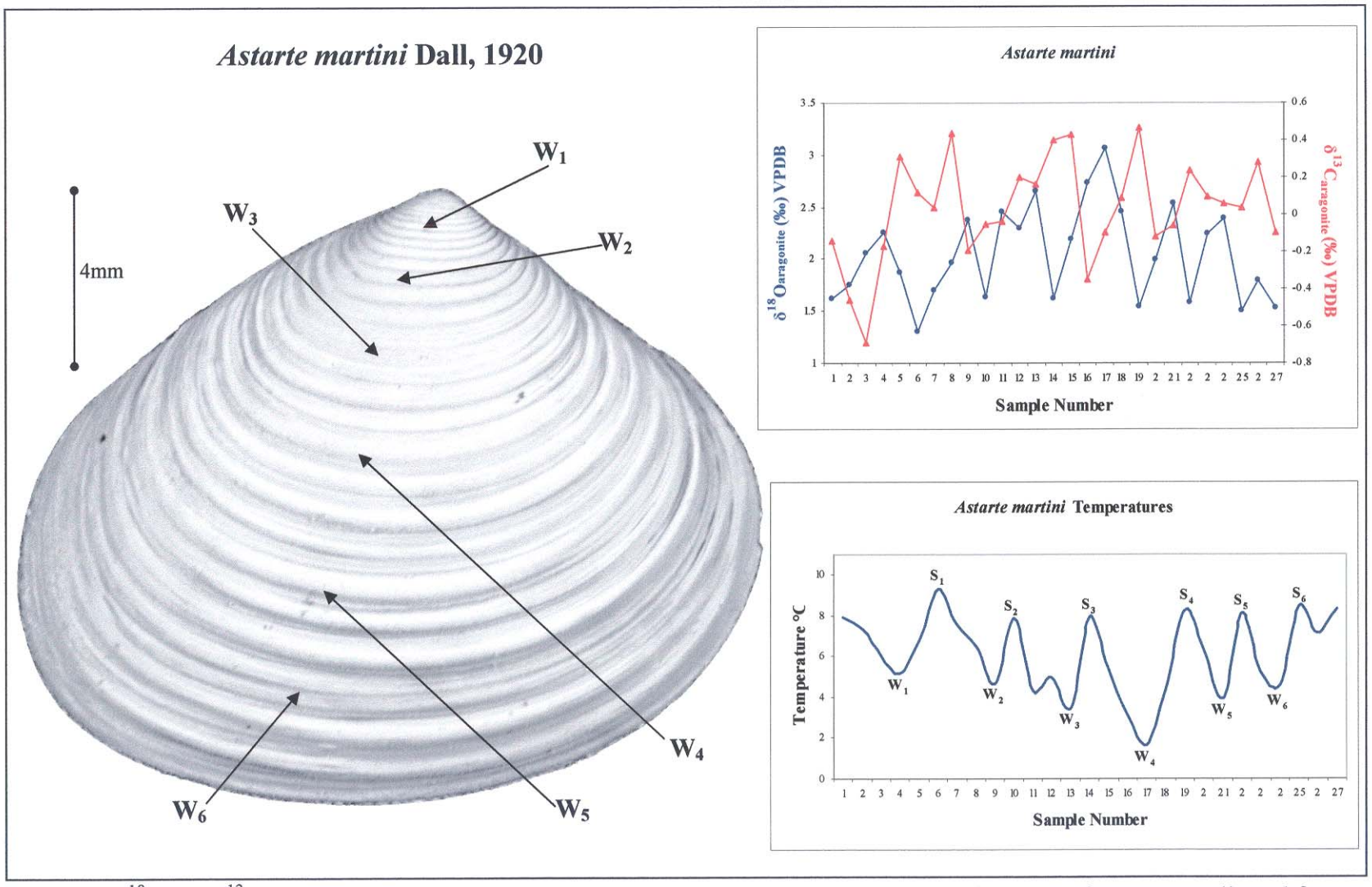

Figure 9. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a fossil specimen of *Astarte cf. martini* collected from the Nuwok Member type locality at Carter Creek, Alaska.

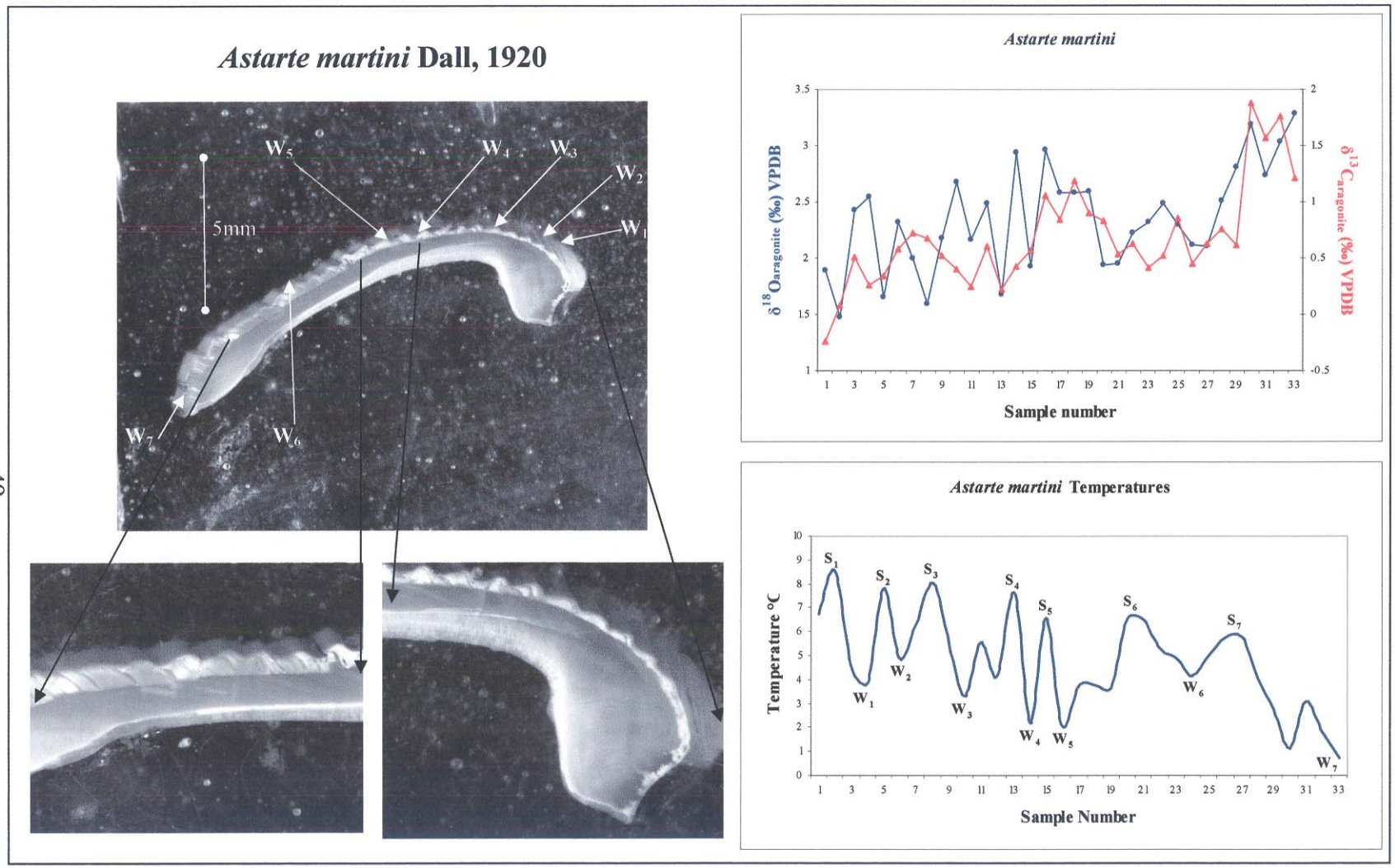

Figure 10. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a fossil specimen of *Astarte martini* collected from the Nuwok Member type locality at Carter Creek, Alaska. This specimen was sampled by an automated micromill device.

shallow isotopically light peaks. This suggests growth was slowed during the cold season for the initial five years followed by rapid, continuous growth. $\delta^{18}O$ values range from 1.48‰ to 3.28‰, with an average of 2.36‰. Ambient water temperatures were calculated using a $\delta^{18}O_{water}$ value of -1.3‰. Calculated paleotemperatures range from 0.7228°C to 8.5348°C, with an average of 4.73269°C.

4.1.4 *Astarte compacta* (Recent)

The recent specimen of *Astarte compacta* was collected by the California Academy of Sciences on August 19, 1954, from the Arctic Ocean, 17 miles west of Arcon Beach, Alaska, from a depth of 91m. The collection location is 71°21'30"N by 157°23'0"W. The specimen was sampled 40 times along the maximum growth axis of 16.83 mm from the dorsal to the ventral margin. The average sample interval was 0.42 mm.

The resulting oxygen isotope profile shows cyclicity with respect to ^{18}O (**Figure 11**). Seven and a half annual growth cycles are displayed as an assymetrical saw tooth pattern. The pattern becomes somewhat cuspate during the last three and a half cycles of growth, suggesting potential cold fronts in the winter and temporary shutdown of shell growth (Wilkinson and Ivany, 2002; Goodwin *et* al., 2003). Isotopically light peaks are more broad and shallow than the isotopically heavy peaks, indicating rapid growth during the warm season and a reduction or cessation in growth during the cold seasons. There does not appear to be a correlation between $\delta^{18}O$ and $\delta^{13}C$ values. $\delta^{18}O$ values ranging from 1.59‰ to 3.12‰, with an average of 2.27‰. Ambient water temperatures were

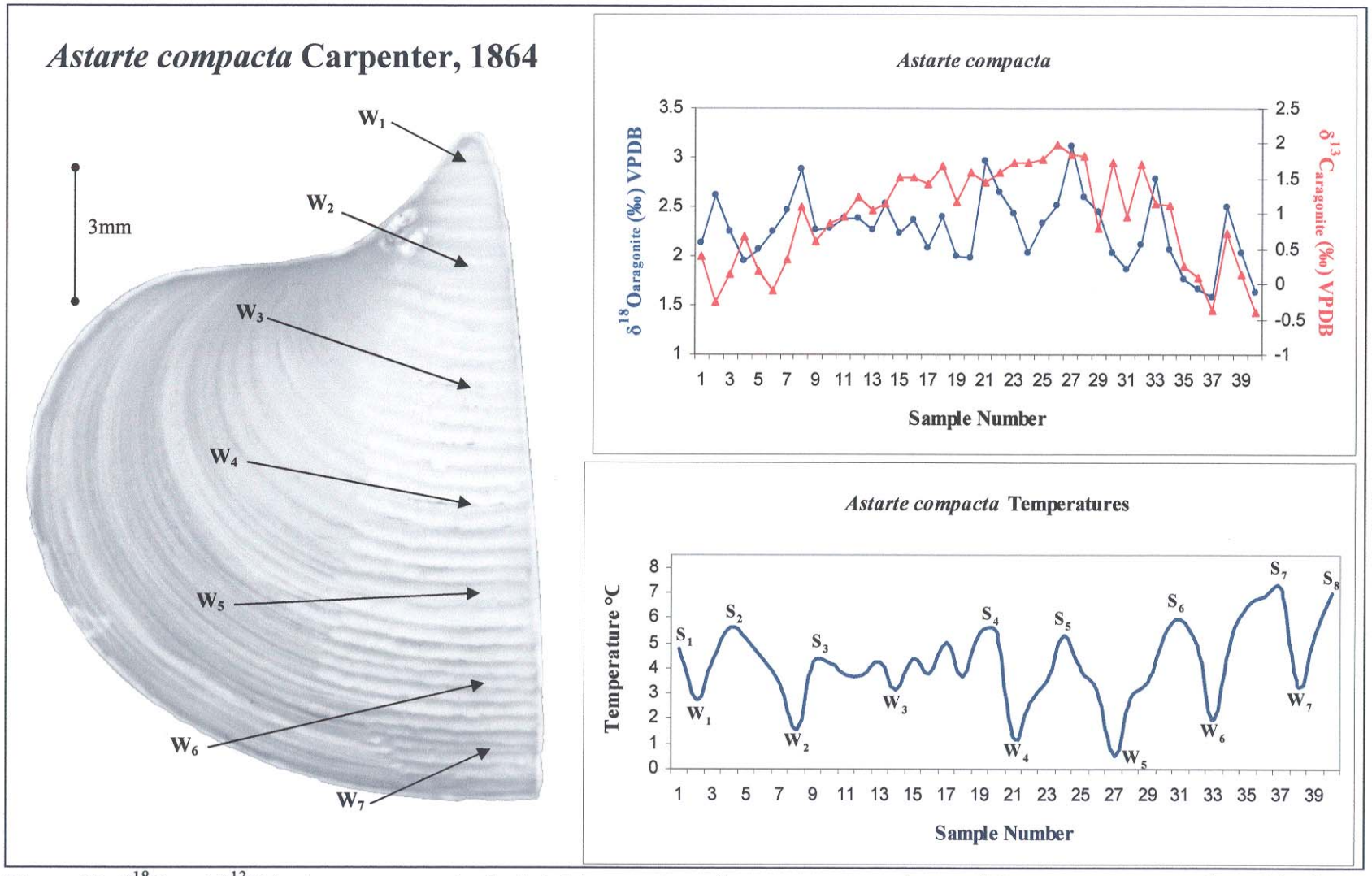

Figure 11. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a recent specimen of *Astarte compacta* collected in the Arctic Ocean, 17 miles west of Arcon Beach, Alaska from a depth of 91m.

calculated using a $\delta^{18}O_{water}$ value of -1.5‰. Calculated paleotemperatures ranged from 0.5492°C to 7.1894°C, with an average of 4.219755°C.

4.1.5 *Macoma cf. calcarea* (Oligocene)

The fossil specimen of *Macoma cf. calcarea* was collected from the limestone layer approximately 40m from the base of the main outcrop at Carter Creek. The shell was sampled 32 times along the maximum growth axis of 23.18 mm from the dorsal to the ventral margin. The average sample interval was 0.72 mm.

The isotopic profile of *M. calcarea* displays an assymetrical saw tooth pattern representing four and a half seasonal growth cycles (**Figure 12**). Seasonality is most pronounced during the first cycle of growth, shown by an isotopically light excursion immediately followed by a heavy excursion between samples one and two. The second year and a half of growth shows a very broad and shallow isotopically light peak, representing an increase in growth rate during the warm season. The remaining two and a half cycles of growth are displayed as a saw tooth pattern with nearly equal heavy and light isotopic excursions, suggesting relatively slowed, but continuous growth. $\delta^{18}O$ values range from 1.11‰ to 3.01‰, with an average of 2.24‰. Ambient water temperatures were calculated using a $\delta^{18}O_{water}$ value of -1.3‰. Calculated paleotemperatures ranged from 1.8946°C to 10.1406°C, with an average of 5.24318°C.

4.1.6 *Arctica carteriana* (Oligocene)

The fossil specimen of *Arctica carteriana* was collected from the limestone layer approximately 40m from the base of the main outcrop at Carter Creek. The shell was

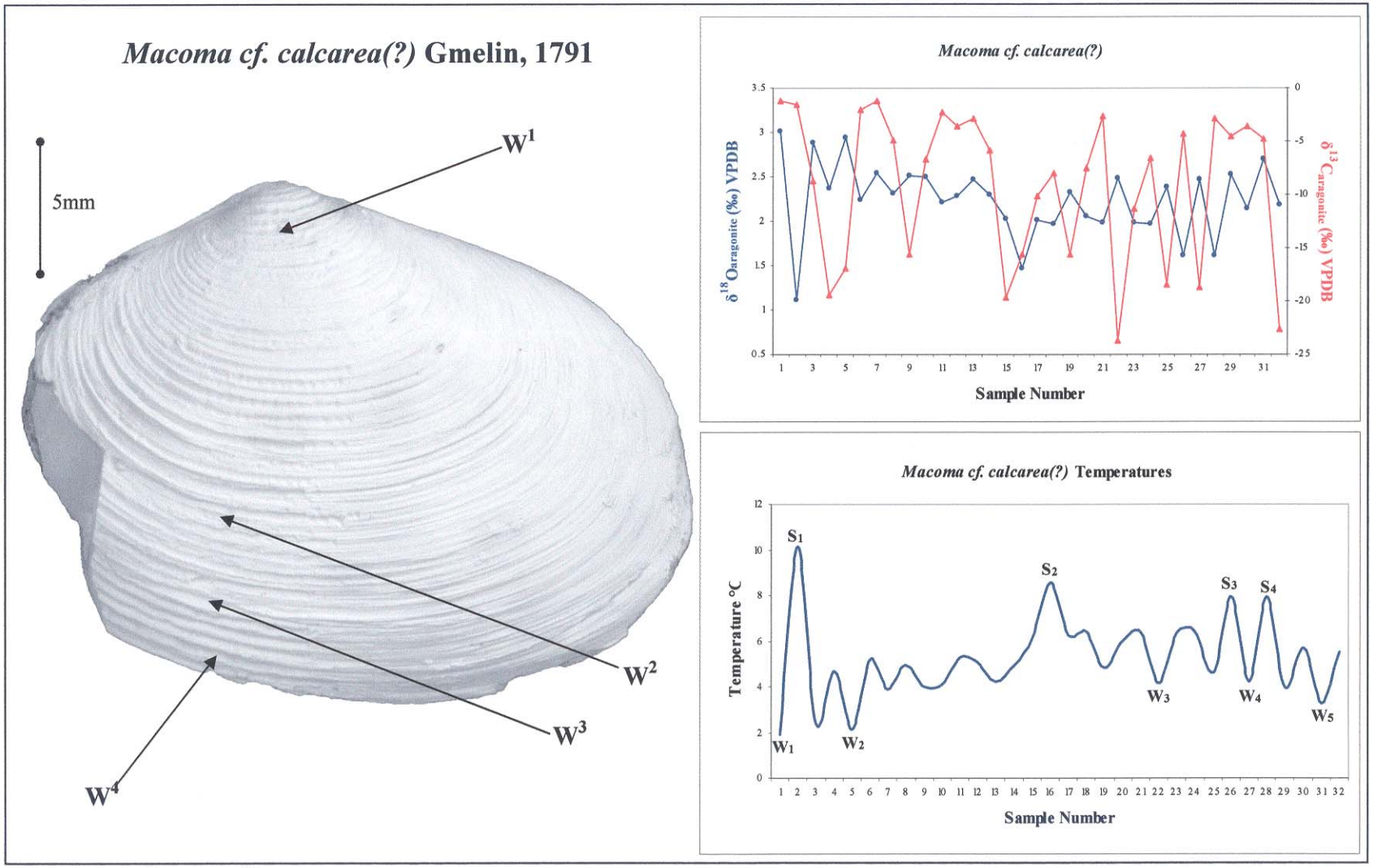

Figure 12. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a fossil specimen of *Macoma cf. calcarea* collected from the Nuwok Member type locality at Carter Creek, Alaska.

sampled 43 times along the maxium growth axis of 52.83 mm from the dorsal to the ventral margin. The average sample interval was 1.23 mm.

The oxygen isotopic profile of *A. carteriana* shows distinct records of seasonality. nine annual cycles of growth are represented (**Figure 13**). Growth bands are difficult, but possible to distinguish. The profile displays as an assymetrical saw tooth pattern with nearly equal heavy and light excursions. Growth appears to have been slow, but continuous throught the year. $\delta^{18}O$ values range from 2.23‰ to 3.21‰, with an average of 2.69‰. Ambient water temperatures were calculated using a $\delta^{18}O_{water}$ value of -1.3‰. Calculated paleotemperatures ranged from 1.0156°C to 5.2765°C, with an average of 3.27056°C.

4.1.7 *Arctica islandica* (Recent)

The recent specimen of *Arctica islandica* (Linnaeus, 1767) was collected by the California Academy of Sciences on June 22, 1974, off the coast of Gufunes, Iceland from a depth of 10 m. The shell was sampled 71 times along the maximum growth axis of 44.32 mm from the dorsal to the ventral margin. The average sample interval was 0.62 mm.

The oxygen isotopic record of *A. islandica* also shows distinct records of seasonality (**Figure 14**). The resulting oxygen isotope data records ten years of growth as a significantly asymmetrical saw tooth pattern. Isotopically light excursions are somewhat shallow and broad suggesting continuous rapid growth throughout the warm season, while isotopically heavy excursions are displayed as narrow peaks indicating short cessation of shell growth during the cold season. $\delta^{18}O$ values range from 1.67‰ to

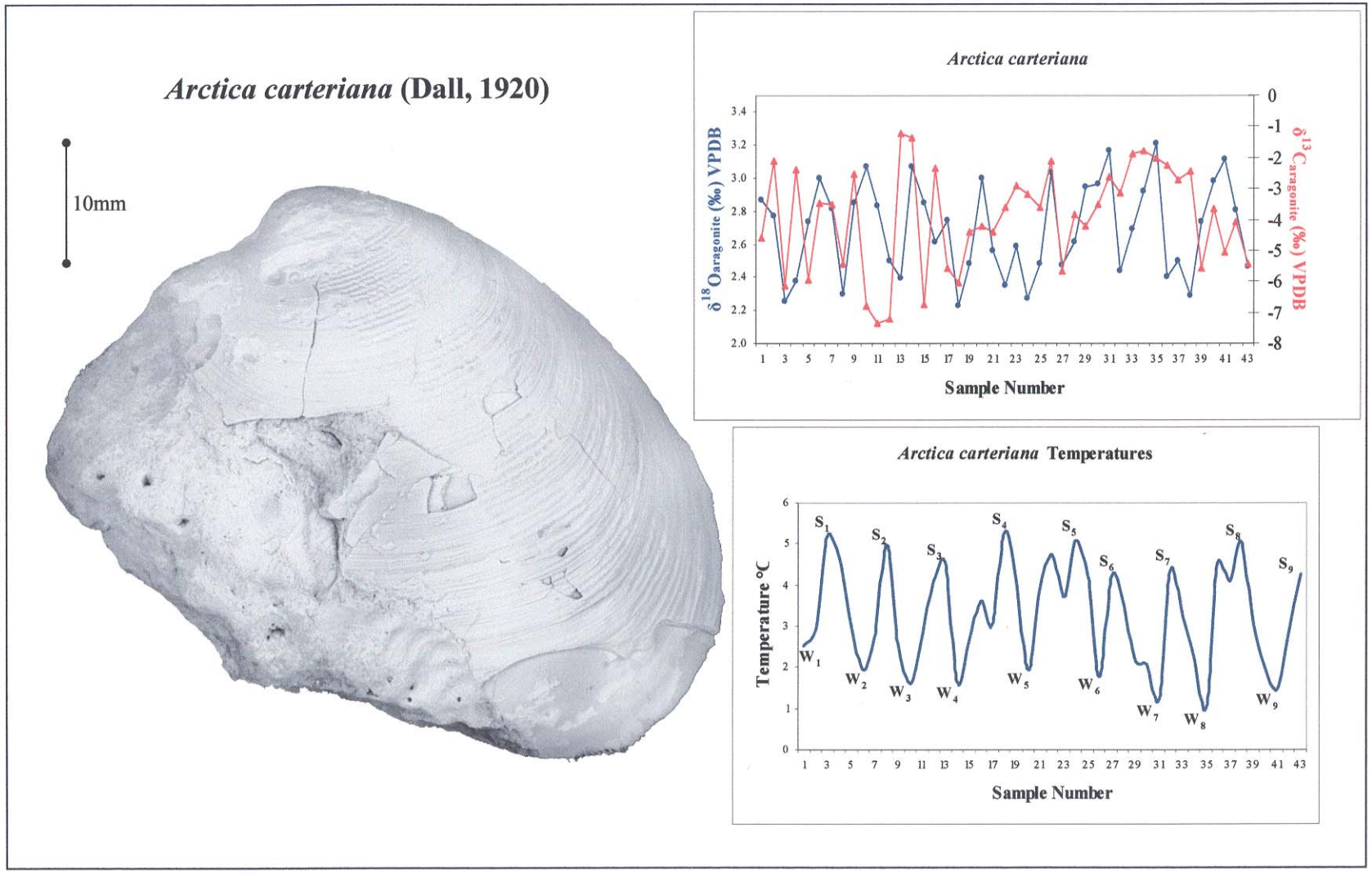

Figure 13. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a fossil specimen of *Arctica carteriana* collected from the Nuwok Member type locality at Carter Creek, Alaska.

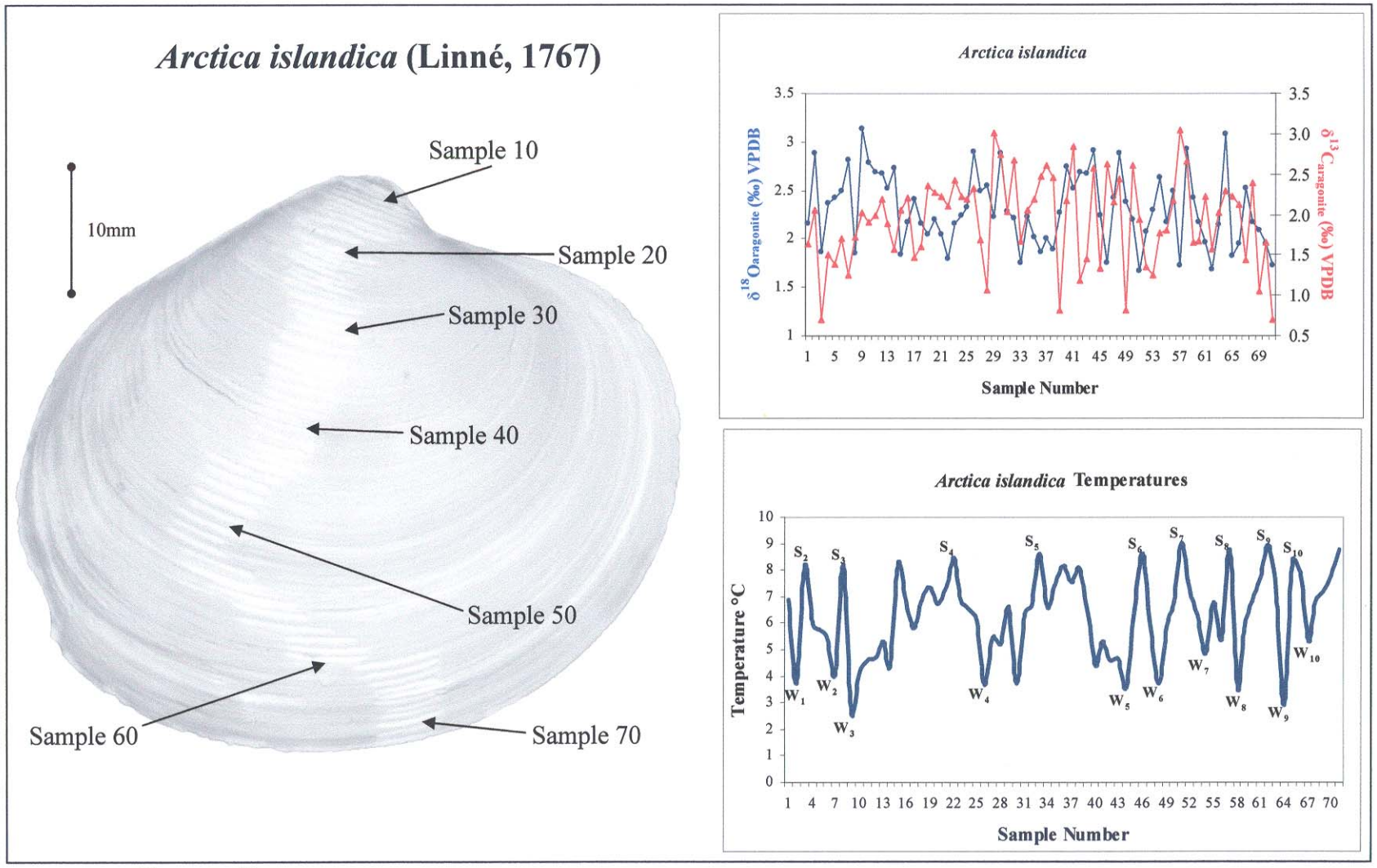

Figure 14. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a recent specimen of *Arctica islandica* collected off the coast of Gufunes, Iceland from a depth of 10 m.

3.14‰, with an average of 2.30‰. Ambient water temperatures were calculated using a $\delta^{18}O_{water}$ value of -1.0‰. Calculated paleotemperatures ranged from 2.6324°C to 9.0112°C, with an average of 6.262718°C.

4.1.8 *Cyrtodaria camdenensis* (Oligocene)

The fossil specimen of *Cyrtodaria camdenensis* was collected from mudstone beds approximately 30m from the base of the main outcrop at Carter Creek. The shell was sampled 26 times along the maxium growth axis of 19.96 mm from the dorsal to the ventral margin. The average sample interval was 0.77 mm.

The resulting oxygen isotope profile displays an assymetrical saw tooth pattern becoming somewhat cuspate, with four especially sharp isotopically heavy excursions, at samples 1, 9, 17, and 25 (**Figure 15**). This suggests brief cessation of growth during cold periods. $\delta^{18}O$ values are relatively enriched throughout the shell transects with values ranging from 2.07‰ to 3.26‰, with an average of 2.65‰. Ambient water temperatures were calculated using a $\delta^{18}O_{water}$ value of -1.3‰. Calculated paleotemperatures ranged from 0.8096°C to 5.9742°C, with an average of 3.47703°C.

4.1.9 *Cyrtodaria kurriana* (Recent)

The recent specimen of *Cyrtodaria kurriana* was collected by the California Academy of Sciences on August 10, 1976, in the Chukchi Sea, at 70°50.00'N and 162°9.00'W from a depth of 32m. The shell was sampled 22 times along the maximum growth axis of 14.01mm from the dorsal to the ventral margin. The average sample interval was 0.64 mm.

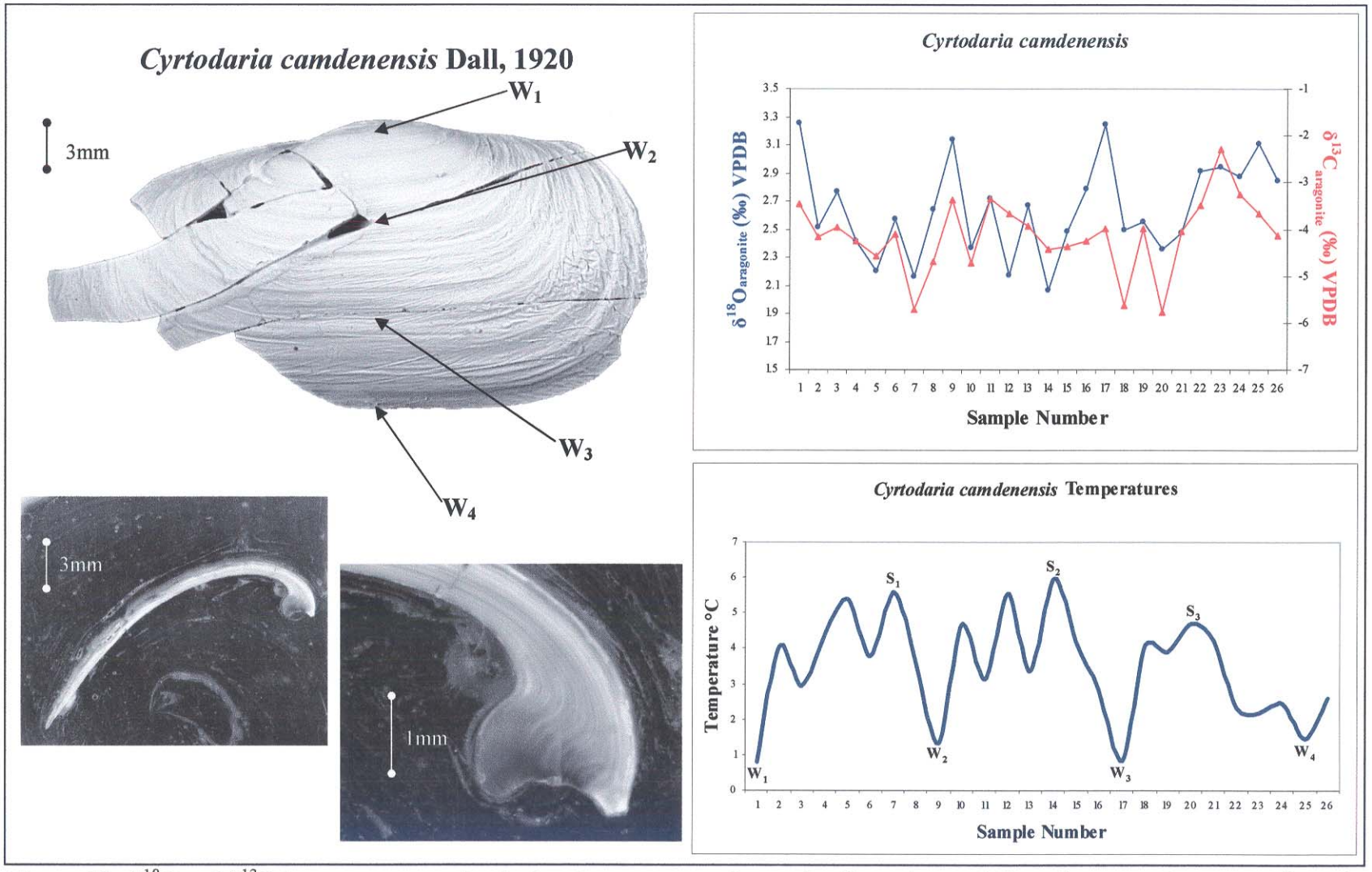

Figure 15. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a fossil specimen of *Cyrtodaria camdenensis* collected from the Nuwok Member type locality at Carter Creek, Alaska.

The isotopic profile of C. kurriana is an extremely assymetrical saw tooth pattern representing two and a half years of growth (**Figure 16**). Growth appears to have been accelerated during the second year as shown by consistenly light oxygen isotopic values across at least five growth bands. There does not appear to be any correlation between ^{18}O and ^{13}C values. The oxygen isotope values range from 0.42‰ to 1.63‰, with an average of 0.94‰. Ambient water temperatures were calculated using a $\delta^{18}O_{water}$ value of -2.45‰. Calculated paleotemperatures ranged from 2.8928°C to 8.1442°C, with an average of 5.90127°C.

4.2 Summary of Isotopic Results

Oxygen stable isotopic analysis of six benthic bivalves from the Nuwok Member of the Sagavanirktok Formation in northern Alaska suggests a seasonal range of late Oligocene sea-surface temperatures from 0.72 to 10.14 °C. A summary of the calculated temperatures is presented in **Table 4**. The average Late Oligocene Arctic Ocean seasonal low was 1.28 °C with temperatures ranging from 0.72 to 1.89 °C among the six fossil specimens analyzed. The average seasonal high was 7.94 °C with temperatures ranging from 5.28 to 10.14°C. *Arctica carteriana* and *Cyrtodaria camdenensis* recorded significantly lower maximum temperatures than the *Macoma, Astarte* and *Thyasira* specimens. Isotopic profiles from all analyzed specimens, recent and fossil, displayed intra-shell cyclicity with respect to $\delta^{18}O$.

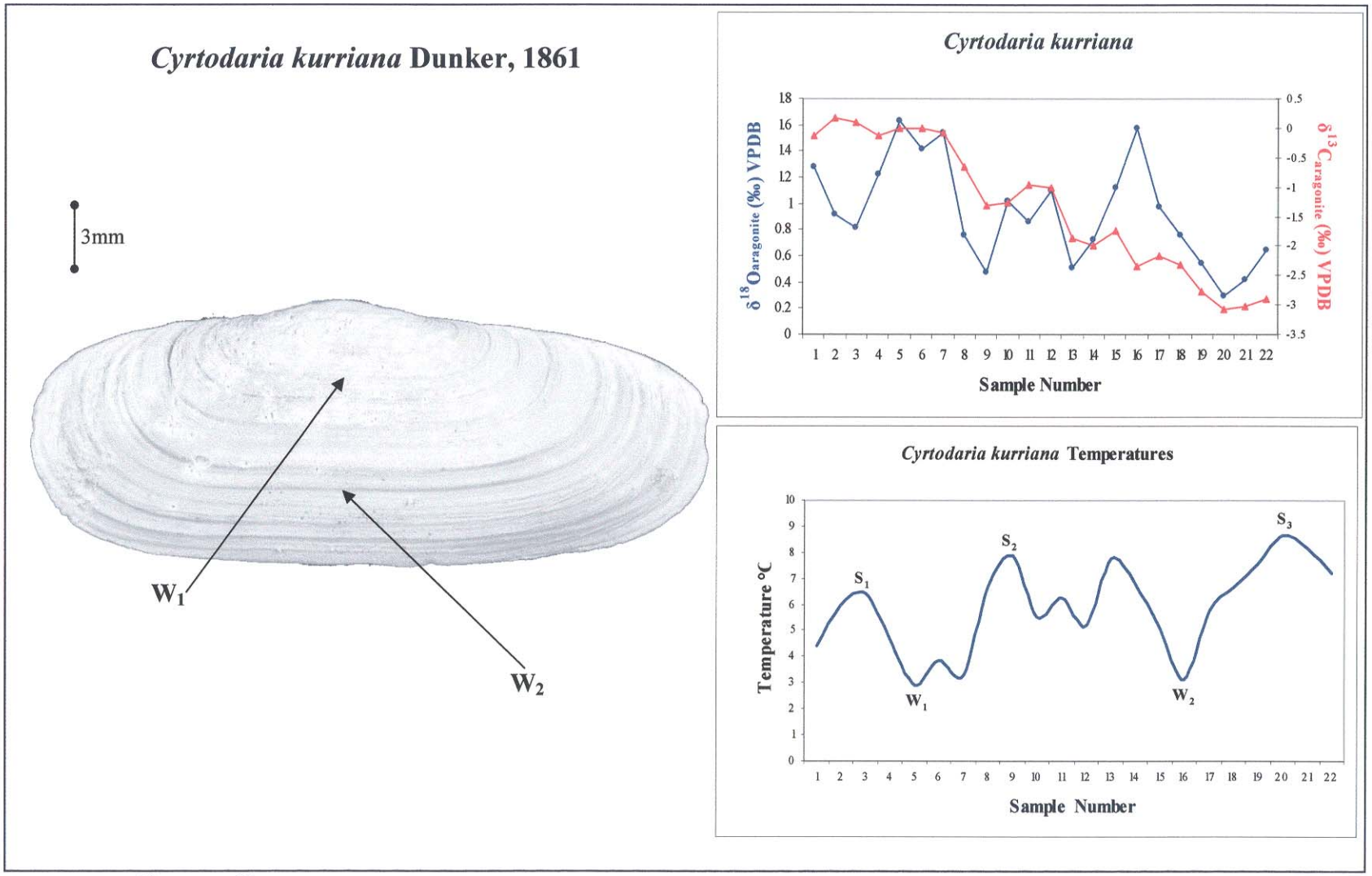

Figure 16. $\delta^{18}O$ and $\delta^{13}C$ isotope curves and calculated temperatures from a recent specimen of *Cyrtodaria kurriana* collected from the Chukchi Sea at a depth of 32m.

Species	Locality	Time Period	Sampling Method	Max $\delta^{18}O$ (‰)	Min $\delta^{18}O$ (‰)	Avg $\delta^{18}O$ (‰)	$\delta^{18}O_{ocean}$ (‰)	Max T (°C)	Min T (°C)	Avg T (°C)
Thyasira alaskana	Carter Creek	Oligocene	hand	3.07	1.50	2.19	-1.30	8.46	1.63	5.47
Thyasira trisinuata	Seattle, Washington	Recent	hand	0.80	-1.87	0.22	-2.50	17.85	6.29	8.79
Astarte martini	Carter Creek	Oligocene	hand	3.07	1.31	2.04	-1.30	9.27	1.63	6.10
Astarte martini	Carter Creek	Oligocene	micromill	3.28	1.48	2.36	-1.30	8.53	0.72	4.73
Astarte compacta	Point Barrow, Alaska	Recent	micromill	3.12	1.59	2.27	-1.50	7.19	0.55	4.22
Macoma cf. calcarea(?)	Carter Creek	Oligocene	hand	3.01	1.11	2.24	-1.30	10.14	1.89	5.24
Arctica carteriana	Carter Creek	Oligocene	hand	3.21	2.23	2.69	-1.30	5.28	1.02	3.27
Arcitca islandica	Gufunes, Iceland	Recent	hand	3.14	1.67	2.30	-1.00	9.01	2.63	6.26
Cyrtodaria camdenensis	Carter Creek	Oligocene	micromill	3.26	2.07	2.65	-1.30	5.97	0.81	3.48
Cyrtodaria kurriana	Chukchi Sea	Recent	micromill	1.63	0.42	0.94	-2.45	8.14	2.89	5.90

Table 4. Summary of Measured Oxygen Isotopic Compositions and Associated Calculated Temperatures

CHAPTER 5

5.0 Systematics

The following sections, 5.1 and 5.2, detail the results of the systematic analysis of the molluscan fossils collected by the author and three fellow researchers, during the summer of 2005, from the type section of the Nuwok Member at Carter Creek, Alaska. Section 5.1 presents systematic descriptions of the Nuwok molluscan fauna. Section 5.2 discusses the biogeography of the fauna based on systematic relationships with coeval and modern, northern, high-latitude faunas.

5.1 Systematic Descriptions

Phylum Mollusca Linné, 1758

Class Gastropoda Cuvier, 1797

Subclass Prosobranchia Milne-Edwards, 1848

Superorder Caenogastropoda Cox, 1959

Order Neotaenioglossa Haller. 1882

Superfamily Rissoacea Gray, 1847

Family Rissoidae Gary, 1847

Genus *Frigidoalvania* Warén, 1974

Frigidoalvania cartercreekensis n.sp.

Plate I, Figures 1, 2

Diagnosis – Shell moderately thick, elongate; rounded whorls separated by deeply impressed sutures; protoconch homeostrophic, smooth; teleoconch with paired strong spiral ribs at upper periphery; aperture nearly round; inner lip thick; outer lip thin

Description – Shell moderately thick, minute, up to 3.60 mm. Spire elevated, with four rounded whorls, separated by deeply impressed sutures. Protoconch of 1 ¾ homeostrophic whorls, smooth, without sculpture. Spiral sculpture of teleoconch whorls consists of strong spiral ribs paired at upper periphery of whorls followed by weak spiral ribs becoming obsolete towards the base of whorls. Ribs separated by interspaces only slightly narrower than ribs themselves. Axial sculpture consists of very fine, closely spaced growth lines. Aperture nearly round, entire marginated, inner lip thickened, outer lip thin; umbilicus absent.

Material Examined – Three moderately well preserved specimens: FAU 700, height 3.60 mm, width 2.00 mm; FAU701, height 2.31 mm, width 1.78 mm; FAU702, height 3.19 mm, width 1.82 mm

Type Locality – Carter Creek, a stream flowing into Camden Bay, Arctic coast of Alaska

Stratigraphic Occurrence – Oligocene: Nuwok Member of the Sagavanirktok Fm., North Slope, Alaska

Distribution –Known only from type locality

Discussion – The shells are very similar in size and form to *Frigidoalvania cruenta* (Odhner, 1915) and *Frigidoalvania scrobiculata* (Möller, 1842), known from the recent

Barents, Kara, Laptev and East Siberian Seas. It differs from *F. cruenta* in having less pronounced and fewer spiral chords toward the base of the whorls and a thinner outer lip. It differs from *F. scrobiculata* in having more pronounced and paired spiral chords at the upper periphery of the whorls and a thinner outer lip. This species may be an ancestor to *F. cruenta* and *F. scrobiculata*, originating in the Late Oligocene Beaufort Sea and subsequently migrating into the Barents, Kara, Laptev and East Siberian Seas. *F. cruenta* and *F. scrobiculata* are not known from the fossil record. This species also modestly resembles *Alvania castanea* Möller, 1842, *A. castanella* Dall, 1886 and *A. dinora* Bartsch, 1917, but has fewer and less uniformly spaced and pronounced spiral chords.

Etymology – The species is named for the type locality

Superfamily Naticacea Forbes, 1838

Family Naticidae Forbes, 1838, p. 29

Subfamily Polinicinae Gray, 1847

Genus *Polinices* Montfort, 1810, pp. 223-224, pl. 56

Subgenus *Euspira* Agassiz in J. Sowerby, 1838, p.14

Polinices (Euspira) pallidus (Broderip and Sowerby, 1829)

Plate I, Figures 3, 4

Natica pallida Broderip and Sowerby, 1829: 372; Gray, 1839: 135, pl. 34, fig. 15; Middendorf, 1849: 421; Middendorf, 1851: 210; Philippi, 1851: 96, pl. 14, fig. 2;

Carpenter, 1864: 523; Sowerby, 1883: 92, pl. 9, fig. 137; Tryon, 1886: 37, pl. 9, figs. 76-78, pl.13, fig. 15, pl. 14, figs. 26-28

Natica pallida forma *normalis* Middendorf, 1851: 210

Lunatia pallida (Broderip and Sowerby), Carpenter, 1864: 661; Dall, 1874: 251; Odhner, 1913: 8, 31-40, pl. 3, figs. 15, 19-37, pl. 4, figs. 1-8, pl. 5, figs. 16-18; Thorson, 1951: 22-23; Okutani, 1964: 393, pl. 1, fig. 19, pl. 5, fig. 8; Okutani, 1966: 16, pl. 2, fig. 6; MacPherson, 1971: 58, pl. 3, fig. 8; Abbott, 1974: 156, fig. 1693; Kantor and Sysoev, 2006: 66, pl. 32E

Polinices (Euspira) pallidus (Broderip and Sowerby), Dall, 1921: 164, pl. 14, fig. 5 [as "*pallida*"]; Oldroyd, 1924: 162, pl. 3, fig. 2 [as "*pallida*"]; Oldroyd, 1927: 728, pl. 97, fig. 9 [as "*pallida*"]; Burch, 1946: 29; Marincovich, 1977: 278, pl. 25, figs. 1-6, 8

Euspira pallida (Broderip and Sowerby), Kuroda and Habe, 1952: 57; Kotaka, 1962: 135, pl. 33, figs. 19-20

Polinices pallidus (Broderip and Sowerby), Pilsbry, 1895: 72; Keen, 1937: 49; MacGinitie, 1959: 91, pl. 12, fig. 10; Clarke, 1963: 97

Eunatica pallida (Broderip and Sowerby), Habe and Ito, 1965: 30, pl. 8, fig. 3

Natica (Lunatia) pallida (Broderip and Sowerby), Friele and Grieg, 1901: 69

Natica groenlandica Möller *ex* Beck MS, 1842a: 80; Möller, 1842b: 7; Jeffreys, 1867: 216; Jeffreys, 1869: 215, pl. 78, fig, 2; Sowerby, 1883: 96, pl. 9, fig. 140; Watson, 1886: 447

Lunatia groenlandica (Möller), Gould, 1870: 341, fig. 611; Sars, 1878: 158, pl. 21, fig. 15, pl. V, fig. 13; Carpenter *in* Dawson, 1872: 392; MacNeil, 1957: 103, pl. 12, fig. 21 [as "aff."]; Bousfield, 1960: 17, pl. 2, fig. 23

Natica (Lunatia) groenlandica Möller, Friele and Grieg, 1901: 69

Polinices groenlandica (Möller), Burch, 1946: 29; Smith and Gordon, 1948: 198 [as "*groenlandicus*"]

Mamma (Lunatia) groenlandica (Möller), Mörch *in* Rink, 1857: 80

Euspira monterona Dall, 1919: 352

Polinices (Euspira) monterona (Dall), Dall, 1921: 164; Oldroyd, 1927: 727; Burch, 1946: 29

Polinices monteronus (Dall), Keen, 1937: 44 [as "*monterona*"]; MacGinitie, 1959: 91, pl. 12, fig. 9

Natica caurina Gould, 1847: 239; Gould, 1852: 212; Gould, 1856: pl. 15, fig. 254; Carpenter, 1875: 209, 213; Gould, 1862: 50, 244; Johnson, 1964: 53, pl. 16, fig. 13

Polinices (Euspira) caurinas (Gould), Dall, 1921: 164 [as "*caurina*"]; Oldroyd, 1924: 162; Oldroyd, 1927: 729; Burch, 1946: 29

Polinices caurinas (Gould), Keen, 1937: 44; Smith and Gordon, 1948: 198

Lunatia caurina (Gould), Woodring, 1938: 22, pl. 5, fig. 19 [as "cf."]; Keen and Bentson,, 1944: 168 [as "cf."]; Adegoke, 1969: 167 [as "cf."]

Euspira canonica Dall, 1919: 353

Polinices (Euspira) canonicus (Dall), Dall, 1921: 165 [as "*canonica*"]; Oldroyd, 1927: 727; Keen, 1937: 44; Burch, 1946: 29

?*Natica borealis* Gray, 1839: 136, pl. 37, fig. 2; Philippi, 1851: 109, pl. 15, fig. 16

Euspira politiana Dall, 1919

Natica pusilla Gould, 1841

Description – Shell thin, globose, small for the species, with moderately elevated spire. Four to five whorls, not greatly inflated, slightly flattened below suture. Spiral sculpture consists of microscopic, wavy, weak costellae; axial sculpture consists of incremental growth lines that are heavier just below suture and on base. Parietal callus thin, slightly filling posterior apertural angle; anterior lobe distinct. Umbilicus narrowly open with a shallow sulcus. Umbilical callus narrow with a very subtle central swelling, expanded posteriorly to bridge umbilicus and meet parietal callus; Funicle inconspicuous. Anterior inner lip and basal lip thickened.

Material Examined – 13 specimens: FAU705, height 6.32 mm, width 6.04 mm; FAU706, height 8.24 mm, width 7.68 mm; Remaining 11 specimens broken, dimensions indeterminate

Type material –

Natica pallida forma *normalis* – Russian Academy of Sciences, Institute of Zoology, St. Petersburg, Russia (Dance, 1966)

Natica groenlandica – Lectotype and paralectotype, Zoological Museum, Copenhagen (Marincovich, 1977)

Euspira monterona – Holotype, USNM 220856

Natica caurina – Lectotype (inadvertently designated by Johnson, 1964), MCZ 169081

Euspira canonica – Holotype, USNM 209411

Type locality –

Natica pallida – Icy Cape (Arctic coast of Alaska) (Broderip and Sowerby, 1829)

Natica pallida forma *normalis* – Southern Sea of Okhotsk and Shantar Island, Russia (Middendorf, 1851)

Natica groenlandica – Greenland (Möller, 1842)

Euspira monterona – USFC station 1199, Captains Bay, Unalaska Island, Alaska, 75 fathoms, mud and gravel (Dall, 1919)

Natica caurina – Straits of Juan de Fuca, Washington (Gould , 1847)

Euspira canonica – USFC station 2923, off San Diego, California, 822 fathoms, green mud (Dall, 1919)

Stratigraphic Occurrence – Ranges from Oligocene to Holocene. Oligocene: Nuwok Member of the Sagavanirktok Fm., North Slope, Alaska. Middle Miocene: Kern River area, California. Middle Miocene to Pliocene: Yakataga Fm., Yakataga area, Alaska. Middle Pliocene: Etchegoin Fm., Coalinga area, California. Upper Pliocene: Rio Dell Fm., Centerville, California. Pliocene: Port Orford Quad., Oregon; Tugidak Island, Trinity Islands, Alsaka. Pliocene to Pleistocene: Tjörnes sequence, Iceland. Lower Pleistocene: Elk River Beds, Oregon; Santa Barbara Fm., California.

Distribution – Circumboreal, circumpolar in the Arctic. Ranges south to Southern California in the east Pacific, Japan in the west Pacific, Cape Hatteras, North Carolina in the west Atlantic and the North Sea and Ireland in the east Atlantic. Modern North

Pacific depth range from shelf to deep water; 0-4794 m. (Golikov and Scarlato, 1967, 1977; Abbot, 1974; Marincovich, 1977; Golikov and Sirenko, 1988)

Discussion – Examined specimens appear small for this species. However, fragments of shell material and internal molds from larger individuals of this species were recovered from the Nuwok Member type locality at Carter Creek. The fragments and molds are not sufficient to identify the individuals with certainty. If they do belong to this species the average size would be much more typical. However, fossils of this species tend to be smaller than living specimens (Marincovich, 1977).

This species resembles *Lunatia heros* (Say, 1822) in its deep, round and open umbilicus, but is much smaller in size and has a thicker parietal callus.

Genus *Choristes* Carpenter, 1872

Choristes cf. carpenteri Dall, 1896

Plate I, Figures 5, 6

Choristes carpenteri Dall, 1896: 10; Dall, 1908: 328, pl. 3, fig. 4; Keen, 1971: 388, fig. 424; Marincovich, 1975: figs. 8,9; Marincovich, 1977: 340, pl. 31, figs. 8-9, text-fig. 11b

Description – Shell whitish, thin, globose, small for the genus, with moderately elevated spire, three preserved rounded whorls, separated by channeled suture; body whorl slightly inflated. Axial sculpture consists of fine slightly oblique incremental growth lines. Parietal callus thin, posterior lobe broken; anterior lobe weak. Umbilicus, although filled with sediment, seems to be completely open, narrow. Inner lip thickened, lacking umbilical callus. Basal lip not thickened. Funicle absent. Spiral costellae absent.

Material Examined – One moderately preserved specimen: FAU 704, height 6.65 mm, Width 5.31 mm

Discussion – Only one *Choristes* specimen was recovered from the Nuwok Member type locality at Carter Creek. The specimen seems most similar to *C. carpenteri* known from the Gulf of Panama, off southernmost Mexico and central Oregon, but it is less than one third its size.

Family Buccinidae Rafinesque, 1815

Genus *Aulacofusus* Dall, 1918

Aulacofusus sp.

Plate I, Figures 7, 8

Description – Shell thin, fusiform, small for genus, up to 34.02 mm. Spire elevated, with 4 ½ rounded, strongly inflated, very slightly shouldered whorls, separated by deeply impressed sutures. Tip of the spire broken in all specimens. Spiral sculpture consists of numerous (7 to 12 between sutures) low, flat-topped, spiral cords; cords are closely, but not always evenly spaced; cords are always thin but slightly thicker cords may alternate with very thin ones. Axial sculpture consists of faint growth lines. Siphonal canal narrow, straight, length is variable from less than ¼ to almost 1/3 of shell height; parietal canal absent. Columella slightly bent. Inner lip with thin and broad callus; outer lip broken on all specimens examined. Aperture occupies a little more than a half of a total length of the shell, rounded at the posterior end and narrowing anteriorly.

Material Examined – 8 specimens, 1 somewhat poorly preserved (FAU711) and 7 poorly preserved (FAU712-718); 49 specimens so poorly preserved and decorticated they may only be considered fragments of individuals or partial casts.

Dimensions – Anterior canals are broken on all measured specimens except for FAU716, height measured may not reflect actual height. FAU711, height 24.24 mm, width 12.63 mm; FAU712, height 14.87 mm, width 9.97 mm; FAU713, height 21.55 mm, width 15.40 mm; FAU714, height 34.02 mm, width 19.86 mm; FAU715, height 28.91 mm, width 16.42 mm; FAU716, height 15.88 mm, width 9.37 mm; FAU717, height 12.06 mm, width 7.39 mm; FAU718, height 8.65 mm, width 4.57 mm.

Stratigraphic Occurrence – Oligocene, Nuwok Member of the Sagavanirktok Formation

Distribution – Genus is circumboreal

Discussion – This form resembles the type species of the genus, *Aulacofusus spitzbergensis* (Reeve, 1855), but differs in being smaller in size, having fewer whorls, and more variability in spacing and thickness of spiral cords. There is also a resemblance to *A. ombronius* (Dall, 1919), but differs in having fewer whorls and uneven spacing of spiral cords. Both *A. spitzbergensis* and *A. ombronius* are documented from the Recent Bering Sea, *A. spitzbergensis* can also be found throughout Arctic Seas to Maine. Several recent species belonging to the family Buccinidae have been described from hydrothermal vents, various kinds of seeps (Warén & Bouchet, 1993; Okutani et al., 1992, 1993; Okutani & Ohta, 1993) and whale skeletons (Naganuma et al., 1996, 1999). Members of this family are proving to be typical inhabitants of environments based on chemosynthetic activities, such as hydrocarbon cold-seeps (Warén & Bouchet, 2001).

Family Turridae Swainson, 1840

Subfamily Turrinae Swainson, 1840

Genus *Antiplanes* Dall, 1902

Antiplanes(?) sp.

Plate I, Figures 9, 10

Description – Shell thin, small for the genus (may be a juvenile specimen), elongated, dextral, with a narrow spire of six rounded and moderately inflated whorls; sutures moderately impressed, but not deep. Protoconch absent from shell. Spiral sculpture not visible. Radial sculpture of very fine growth lines with a faint, shallowly u-shaped sinus. Aperture ovate-oblong; anterior canal short, flexed. Outer lip broken, but appears thin; smooth inside; unable to distinguish "turrid notch". Columella broadly sigmoid and slightly thickened.

Material Examined – One decorticated specimen: FAU703, height 17.25 mm, width 6.46 mm

Distribution – *Antiplanes* is documented in the moderate to deep cold waters off the Californian coast to Alaska and around the Bering Sea to Kamchatka and Japan (Powell, 1966).

Discussion – Only one *Antiplanes* specimen was collected from the Nuwok Member type section at Carter Creek. Unfortunately, the shell is so poorly preserved there is very little ability to compare to other *Antiplanes* species. Except for the very faint remnants of a growth line sinus all other sculpture has been worn away. This shell somewhat resembles

A. santarosana (Dall, 1902) in shape, but has fewer whorls, a shorter anterior canal, and a wider aperture. *A. santarosana* is found off Santa Rosa Island and from Point Sur to off San Diego, California. There is also a resemblance to *A. dendritoplicata* Kantor and Sysoev, 1991 and *A. sanctiioannis* (E.A. Smith, 1875) reported from the Okhotsk Sea and the Bering to Japan Seas, respectively. This form differs in being roughly half the size of *A. dendritoplicata* and *A. sanctiioannis*, and having a shorter anterior canal.

Antiplanes are well documented in the fossil record from post-Pliocene deposits in California localities and are claimed from the Lattorfian Oligocene of Germany (Powell, 1966). The discovery of *Antiplanes* from Late Oligocene northern Alaska may be an indication of the timeline and migratory path of the genus from the northeastern Atlantic through the Arctic and into northeastern Pacific waters.

Superfamily Cylichnacea A. Adams, 1850

Family Cylichnidae A. Adams, 1850

Genus *Scaphander* Montfort, 1810

Scaphander aff. Lignarius (Linné, 1758)

Plate I, Figures 11, 12

Scaphander aff. Lignarius (Linné), MacNeil, 1957: 103, pl. 11, Figs. 2, 10

Description – Shell of average size for the genus, ovate-oblong, spire involute, apex slightly sunken. Aperture restricted posteriorly, opens roundly anteriorly with a slightly thickened columella. Sculpture smooth with faint growth lines and closely, uniformly spaced, thin, incised spiral striations.

Material Examined – 3 poorly preserved specimens: FAU734, height 31.85mm, width 18.83mm; FAU735, height 28.63mm, width 17.62mm; FAU736, height 38.61mm, width 22.05mm

Stratigraphic occurrence – Oligocene: Nuwok Member of the Sagavanirktok Fm., North Slope, Alaska; Pliocene: England, Belgium, Holland, France, and Italy; Pleistocene: England (MacNeil, 1957)

Distribution - Norway to the Mediterranean and Azores (MacNeil, 1957; Kantor and Sysoev, 2006)

Discussion – *S. lignarius* has simple or wavy well separated incised spiral lines which distinguishes it from the more bulbous *S. punctostriatus* and *S. nobilis* which have rows of punctuations rather than continuous incised lines (MacNeil, 1957; Abbott, 1974). Spiral lines of the Carter Creek specimens are more numerous and more closely spaced than in the typical *S. lignarius* (MacNeil, 1957).

The genus is widely distributed throughout the Tertiary. Two species of large *Scaphander*, also with the incised spiral lines, have been described from the Oligocene of Washington and southern Alaska, *S. washingtonensis* and *S. alaskensis*. Spiral lines of *S. alaskensis* are paired and so deep and broad that the interspaces are best described as raised spiral threads (MacNeil, 1957). However, the shape and apical characters are almost identical to the Carter Creek specimens. *S. conradi* from the Empire Formation (Pliocene) of Oregon resembles the Carter Creek specimens, but its spiral lines are punctuated (MacNeil, 1957). No *Scaphander* resembling the form of *S. lignarius* have been found pre-Oligocene; the origin of the *S. lignarius* group remains debatable.

Class Scaphapoda Bronn, 1862

Family Dentaliidae Gray, 1834

Genus *Cadulus* Philippi, 1844

Cadulus arcticus Dall, 1920

Plate I, Figure 13

Cadulus arcticus Dall, 1920: 30, pl. V, fig. 8

?Cadulus arcticus MacNeil, 1957: 107, pl. 12, fig. 27

Original Description – Shell small, slender, arcuate, smooth, with circular section and no swelling ventrally; the color is white with narrow translucent zones irregularly disposed

Material Examined – 2 specimens: FAU745, 5.64mm; FAU746, 4.43 mm

Type material – Holotype, USNM 324322

Type locality – USGS Tertiary Location 7070, Carter Creek, a stream flowing into Camden Bay, Arctic coast of Alaska

Stratigraphic occurrence – Oligocene: Nuwok Member of the Sagavanirktok Fm., North Slope, Alaska

Distribution – Known only from type locality

Discussion – Little is known regarding Arctic Alaskan scaphopods. No records of eastern Arctic Ocean scaphapods have been found, although a number of species are documented from the western Arctic Ocean (Emerson, in MacNeil, 1957). *C. arcticus* shares some characteristics with *Siphonodentalium (Pulsellum)* species; it is similar in shape and lacks apical slits. However, *C. arcticus* is larger than all species of this

subgenus except the Japanese species, *S. (Pulsellum) ozawai* Yokoyama, 1926. They appear to be similar in form and size, and may be related. *S. (Pulsellum) ozowai* is documented from the Sawané Pliocene to Recent.

Class Bivalvia Linné, 1758

Subclass Palaeotoxodonta Korobkov, 1954

Order Nuculoida Dall, 1889

Superfamily Nuculacea Gray, 1824

Family Nuculidae Gray, 1824

Genus *Nucula* Lamarck, 1799

Nucula sp.

Plate II, Figure 1

Description – Shell large for genus, ovate. Sculpture and shell material almost entirely worn away; concentric sculpture of fine, irregular lirae visible on some specimens; radial sculpture absent. Outer shell material chalky, white with some preserved dark brown perisostracum; remnants of nacreous interior visible on surface of internal mold. Hinge plate strong, with anterior and posterior series of numerous, large, similar, taxodont teeth. Lunule strong, wide; remains of escutcheon on one specimen appears to be long.

Material Examined – Hinge teeth and partial internal molds of 3 specimens: FAU747, FAU748, FAU749, dimensions indeterminate

Stratigraphic occurrence – Oligocene: Nuwok Member, North Slope, Alaska

Discussion – A Carter Creek *Nucula* was identified by Dall (1920) as *N. variabilis*, subgenus *Acila*. However, there are not enough diagnostic features to relate the three specimens collected for this study to a particular *Nucula* species. It is listed here as *Nucula sp.* because of the shape of the internal mold, the nacreous interior and features of the hinge. There seems to be some similarity in shape and sculpture to *Nucula (Leionucula) belloti* Adams, 1856 found in the Arctic and Greenland.

Superfamily Nuculanacea H. and A. Adams, 1858

Family Nuculanidae Meek, 1864

Genus *Nuculana* Link, 1807

Nuculana morrisi MacNeil, 1957

Plate II, Figure 2

Nuculana morrisi MacNeil, 1957: 120, pl.11, fig. 3

Description – Shell of medium size for genus; sharply rounded anteriorly but moderately blunt; minimally attenuated posteriorly. Beaks low, but distinct and situated at about four-sevenths the distance from the posterior end. Valves slightly inflated, giving shell a fat appearance. Anterior dorsal margin weakly convex; posterior dorsal margin very weakly concave or straight. Posterior part of shell has a well-defined nearly straight dorsal truncation just below the dorsal margin and a weaker angulation, also nearly straight or very slightly curved extending in the posterior-ventral direction, the two forming a weak but broad sulcate area between them. Sculpture consists of sharp raised concentric lirations which, on the anterior side, have a steeper dorsal slope, but which are

higher, narrower, and nearly symmetrical on the posterior side. Hinge nearly straight; chondrophore small; escutcheon long and narrow.

Type material – Holotype: USNM 561865

Material Examined – 5 poorly preserved specimen: FAU742, height 11.41 mm, length 19.63 mm; FAU743, height 7.15 mm, length 15.01 mm; FAU744, height 13.20 mm, length 26.54 mm; FAU750, measurements indeterminate, FAU751, measurements indeterminate

Type locality – Carter Creek, a stream flowing into Camden Bay, Arctic coast of Alaska.

Stratigraphic Occurrence – Oligocene: Nuwok Member of the Sagavanirktok Fm., North Slope, Alaska

Distribution – Known only from type locality

Discussion – *N. morrisi* may be related to *N. leonina* a recent, deep water species found off the northwest coast of the United States with a slightly higher beak and much more concave posterior dorsal margin (MacNeil, 1957). *N. morrisi* is also similar to the recent groups of *N. pernula*, *N. minuta and N. lamelosa*, except it is broader and less attenuated posteriorly (MacNeil, 1957). A similar fossil species, *N. washingtonensis* is described from Oligocene, Washington, Lincoln Fm.; *N. morrisi* is less attenuated posteriorly (MacNeil, 1957). *N. morrisi* has a weak, but distinct posterior radial sulcus, differentiating it from the aforementioned, otherwise similar *Nuculana* species.

Subclass Cryptodonta Neumayr, 1884

Order Solemyoida Dall, 1889

Superfamily Solemyacea H. and A. Adams, 1857

Family Solemyacidae H. and A. Adams, 1857

Genus *Solemya* Lamarck, 1818

Solemya sp.

Plate II, Figure 3

Description – Shell large for genus, oblong. Hinge and dorsal margin not visible, posterior margin broken. Outer shell layers mostly worn, visible sculpture consists of widely spaced dark radial bands; faint, undulating, growth lines visible.

Material Examined –One valve from one poorly preserved specimen: FAU752, height indeterminate, length 64.4 mm

Stratigraphic occurrence – Oligocene: Nuwok Member, North Slope, Alaska

Distribution – Current distribution for the genus is North Pacific at depths ranging from 300-600 m with plant debris (Marincovich, personal communication)

Discussion – This form is similar in size and may be related to the recent, boreal, Atlantic species, *S. borealis*. Relationships are uncertain due to the lack of well preserved specimens from Carter Creek.

Subclass Pteriomorpha Beurlen, 1944

Order Arcoida Stoliczka, 1871

Superfamily Arcacea Lamarck, 1809

Family Arcidae Lamarck, 1809

Subfamily Arcinae Lamarck, 1809

Genus *Barbatia* Gray, 1842

Subgenus *Barbatia* Gray, 1842

Barbatia (Barbatia)(?) sp.

Plate II, Figures 4, 5

Diagnosis – Shell sub-quadrate, compressed with a straight hinge and flat, narrow and long cardinal area. Umbos not prominent. Sculpture cancellate.

Description – Shell sub-quadrate, elongate , slightly compressed, small for the subgenus. Umbos not prominent, situated two-thirds the distance from the posterior end, separated by a narrow, long, flattened cardinal area. Hinge plate straight. Sculpture cancellate, with low, narrow, regularly spaced radial ribs diminishing towards the dorsal margin and near umbo; concentric sculpture of irregular fine striae.

Material Examined – 2 specimens: FAU753, height 5.33 mm, length 9.74 mm; FAU754, height 3.36 mm, length 6.23 mm

Stratigraphic occurrence – Oligocene: Nuwok Member, North Slope, Alaska

Discussion – *Barbatia* species are predominantly found in warm water, as are the majority of members of the family Arcidae. The discovery of *Barbatia* in the Late Oligocene Arctic Ocean is unexpected. This form is much smaller and has a thinner shell than other *Barbatia* species. There is some similarity to *Barbatia cancellaria* (Lamarch, 1819), but it is two to three times larger. The genus *Obliquarca* is a junior synonym for *Barbatia*. *Obliquarca* is a well documented fossil, endemic Arctic group from the warm Eocene. It is likely the Nuwok specimen is a relict from the Eocene. These shells are also similar to species of the genus *Arcopsis*, which are also only found in warm water.

In particular, the shells from Carter Creek closely resemble *A. adamsi* (Dall, 1886) in size, shape and sculpture, but are slightly more elongate. Differentiation between *Barbatia* and *Arcopsis* requires observation of the ligament, which was unfortunately not preserved with the specimens.

Subfamily Anadarinae Reinhart, 1935

Genus *Bathyarca* Kobelt, 1891

Bathyarca sp.

Plate II, Figures 6, 7

Diagnosis – Shell small, inflated, ovate. Umbos subcentral. Hinge line straight with narrow cardinal area. Sculpture of radial and concentric striae.

Description – Shell obliquely ovate, longer than high, inflated. Valves are equal but inequilateral. Umbones subcentral, prominent. Dorsal margin straight, squared at ends. Cancellate sculpture of fine concentric and radial striae. Hinge plate straight, cardinal area short and narrow.

Material Examined – 2 specimens: FAU755, height 4.55 mm, length 5.88 mm; FAU756, height 3.59 mm, length 4.75 mm

Discussion – The shells are very similar in size and shape to *Bathyarca frielei* (Friele, 1877) and *B. nucleator* (Dall, 1908), known from the Arctic and the North Pacific, respectively. It differs from *B. frielei* in being more ovate and from *B. nucleator* in being more oblique and inequilateral.

Superfamily Limopsacea Dall, 1895

Family Limopsidae Dall, 1895

Genus *Limopsis* Sassi, 1827

Limopsis aff. panamensis Dall, 1902

Plate II, Figures 8, 9

Limopsis panamensis Dall, 1902: 559; Coan et al., 2000: 147, pl. 21

Limopsis diegensis Dall, 1908: 395; Abbott, 1974: 426, fig. 5011

Limopsis juarezi Dall, 1908: 396

Limopsis stimpsoni Dall, 1908: 396

Limopsis diazi Dall, 1908: 397

Description – Shell small, ovate, oblique, subequilateral, somewhat inflated. Hinge plate short, narrow, nearly straight; teeth broken except for one large anterior tooth and two slightly smaller posterior teeth, demonstrating subequal, two series nature of hinge teeth. Inner ventral margin crenulate with weak internal radial sculpture; external sculpture reticulate with concentric striae overlapping thin radial ribs.

Material Examined – One moderately well preserved specimen: FAU710, height 5.32 mm, length 5.61 mm

Stratigraphic occurrence – Oligocene: Nuwok Member, North Slope, Alaska. Genus is known from early Cretaceous (Coan et al., 2000)

Distribution – Locally abundant, from Tufts Abyssal Plain, Oregon, to Isla Cedros, Baja California, to Panama, in 130 – 3,900 m. (Coan et al., 2000)

Discussion – Only one valve from a single *Limopsis* specimen was recovered during this study. It seems to be most similar to *L. panamensis*, differing by being only slightly more oblique. There is also some similarity to *L. akutanica* Dall, 1916 and *L. tenella* Jeffreys, 1876, found as far north as Adak Island. The Carter Creek specimen differs from *L. akutanica* in its narrower hinge plate and differs from *L. tenella* in its shorter hinge plate. Prior to this discovery, *Limopsis* have not been documented in the Arctic outside of the Bering Sea.

Suborder Pteriina Newell, 1965

Superfamily Pectinacea Rafinesque, 1815

Family Pectinidae Rafinesque, 1815

Subfamily Chlamydinae Korobkov, 1960

Genus *Chlamys* Röding, 1798

Chlamys Nuwokensis MacNeil, 1957

Plate II, Figures 10-13

Chlamys nuwokensis MacNeil, 1957: 120, pl. 11, figs. 4-6, 12

Original Description – Shell of medium size, suborbicular; valves very little inflated, very thin. Dorsal margins concave, the posterior margin a little more so than the anterior margin and terminating in a line more nearly horizontal. Posterior margin of posterior ears strongly sloping; anterior margin of anterior ear of left valve about vertical; anterior ear of right valve alate with moderate byssal sinus. Dorsal margin along byssal sinus bearing strong denticles. No well-defined submarginal areas. Sculpture similar on both

valves but ribs on right valve may be slightly broader at the crest. Nine well-formed ribs on each valve and on some individuals another incipient rib at either end or both ends. Ribs narrow and some bluntly rounded on top, separated by broad evenly concave interspaces that rise gently to the crest of the ribs. Secondary radial lirations in the interspaces, and in individuals whose ribs are not flattened on top may be present on top of the ribs as well; 8 to 14 secondary radial lirations in each interspace. The alate anterior ear of the right valve with 3 to 4 strong radials; all other ears sculptured with fine lirations similar to the secondary lirations on the disc but sometimes made beaded by growth lines. Raised slightly irregular concentric lamellae extend across the crest of the ribs and on the secondary radial lirations form tiny upright crescentic spines. The ligament pit is shallow and inclined slightly to the posterior.

Material Examined – 9 specimens, all measurements indeterminate: FAU757, broken right valve; FAU758, broken left valve; the beak portion of the shell from 3 right valves and 3 left valves. 10 partial impressions, all with whitish to nacreous looking outer layer of shell left in impression. 25 partial internal molds, some with remnants of original shell material, all with nacreous remains of inner shell layer: 4 internal molds of both valves; 21 internal molds of single valves.

Type material – Holotype: left valve, USNM 561866 Paratype: 2 left valves, USNM 561867, USNM 561868; 1 right valve, USNM 561869

Type locality – USGS station D50, Carter Creek, a stream flowing into Camden Bay, Arctic coast of Alaska.

Stratigraphic Occurrence – Oligocene: Nuwok Member, North Slope, Alaska

Distribution – Known only from type locality

Discussion – Prior to this discovery, members of the genus *Chlamys* were known as far back as the Miocene. *C. nuwokensis* resembles *C. Sayanus* Dall, from the Miocene of Florida, with its concave dorsal margin, scabrous surface and rib pattern (MacNeil, 1957). There is also a resemblance to *C. virginianus* (Conrad), from the Miocene of Virginia, but differs in having primary ribs only near the beaks (MacNeil, 1957). The ribbing of the left valve of *C. nuwokensis* resembles that of *Fortipecten hallae* (Dall), from the Pliocene or Pleistocene of Nome, Alaska; *F. hallae* has a much heavier shell and the sculpture of the right valve is much different (MacNeil, 1957).

Genus *Palliolum* Monterosato, 1884

Palliolum groenlandicum (Sowerby)

Plate II, Figures 14, 15

Palliolum groenlandicum (Sowerby), Soot-Ryen, 1932; MacNeil, 1957: 104, pl.11, figs. 17-18

Description – Shell small, orbicular, very thin and translucent. Dorsal margin straight. Anterior ears slightly longer than posterior; anterior ear of right valve alate with moderate byssal sinus. Right valve with very fine concentric lines and irregularly spaced, wide, very low, axial bands. Left valve with very fine concentric lines and numerous, thin, wavy, very slightly raised and rounded axial lines.

Material Examined – 3 whole specimens, both valves: FAU759, height 8.11 mm,length 8.02 mm; FAU760, height 9.92 mm, length 9.86 mm; FAU761, height 11.35 mm, length 11.49 mm . 16 single, broken valves, measurements indeterminate.

Stratigraphic occurrence – Oligocene: Nuwok Member, North Slope, Alaska

Distribution – East Siberian Sea westward to Norway, in the Atlantic south to Sudan in Africa and the Gulf of Saint Lawrence, and Greenland west to Dolphin and Union Strait (Soot-Ryen, 1932)

Discussion – It is not known in the Chukchi and Beaufort Seas, Bering Sea or the Pacific. Its occurrence as a fossil in the Camden Bay area, near the center of the region where it does not now occur may indicate either that it was once circumarctic or that this was a migration from the east, just as its recent occurrence in the East Siberian Sea may be a penetration from the west" (MacNeil, 1957, p. 104).

Subclass Heterodonta Neumayr, 1884

Order Veneroida H. and A. Adams, 1856

Superfamily Lucinacea Fleming, 1828

Family Thyasiridae Dall, 1901

Genus *Thyasira* Lamarck, 1818

Thyasira alaskana (Kaufman, 1969)

Plate III, Figures 1,2

Description – Shell average size for genus, subtrigonal to orbicular, height slightly greater than length. Valves are moderately inflated; umbones prominent, prosogyrate;

escutcheon deep and narrow. Sculpture of very fine concentric lirae. Posterior end separated by a deep radial sulcus.

Material Examined – 4 whole specimens with both valves: FAU762, height 25.9 mm, length 25.53 mm; FAU763, height 25.75 mm, length 25.24 mm;FAU764, height 34.92 mm, length 34.51 mm; FAU765, height 29.01 mm, length 29.77 mm. 26 broken specimens, measurement indeterminate

Stratigraphic occurrence – Ranges from Oligocene to Pliocene in the Arctic and Atlantic.

Discussion – *Thyasira alaskana* seems to occupy "an evolutionary position midway between Cretaceous and Recent species and denotes a continuation of the trends toward more efficient burrowing forms" (Kaufman, 1969). Kaufman (1969) relates *T. alaskana* to the Late Cretaceous *T. advena-T. becca* species group of Western Interior North America. MacNeil (1957) relates the Carter Creek *Thyasira* to the living species group of *T. sarsii* (Philippi) and *T. arctica* Soot-Ryen by reason of shell size and rotund shape. Abbott (1974) and MacGinitie (1959) both consider *T. sarsii* to be a form of *T. flexuosa* (Montagu, 1803). Of the recent *Thyasira* species, *T. flexuosa* most closely resembles the *Thyasira alaskana* specimens collected at Carter Creek. *T. Flexuosa* is currently common offshore to 60 fathoms and found on both Atlantic coasts, from Greenland to off North Carolina, and from the Bering Sea to off San Diego (Abbott, 1974). *T. flexuosa* is circumboreal and panarctic (Coan et al., 200). MacGinitie (1959) reports recovering *T. flexuosa* from 162 feet.

Superfamily Crassatellacea Fleming, 1820

Family Astartidae Orbigny, 1844

Genus *Astarte* Sowerby, 1816

Subgenus *Astarte* Sowerby, 1816

Astarte martini Dall, 1920

Plate IV, Figures 1, 2

Astarte martini Dall, 1920: 32, pl. VI, fig. 12; MacNeil, 1957: pl. 12, fig. 7

Original Description – Shell small, ovate, with inconspicuous pointed beaks, dorsal slopes straight, anterior end rounded, shorter, base evenly arcuate, posterior end slightly longer, attenuated and almost obliquely truncated; a narrow elongate escutcheon and shorter, narrower, slightly excavated lunule present; sculpture of somewhat irregular, slightly raised, close set, concentric, narrow wavelets, becoming almost lamellose near the edge of the lunule; and in other specimens reduced to narrow threads on the disk; hinge heavy, normal, muscular impressions somewhat excavated, inner margin smooth or crenulate.

Material Examined – 33 valves: average height 26.24 mm, length 20.12 mm

Type material – USNM324307

Type locality – USGS Staion 7231, Carter Creek, a stream flowing into Camden Bay, Arctic Coast of Alaska

Stratigraphic occurrence – Oligocene: Nuwok Member, North Slope, Alaska

Distribution – Known only from the type locality

Discussion – *Astarte martini* is probably related to the currently circumboreal and panarctic, *A. crenata* (Gray, 1824). *A. crenata* differs in being shorter (MacNeil, 1957). Also, not all examined specimens of *A. martini* had a crenulate inner ventral margin, a diagnostic feature of *A. crenata*. Other species related to *A. crenata*, such as *A. concentrica* Conrad, *A. galeotti* Nyst, *A. gracilis* Munster, *A. sulcata* (DaCosta) and *A. incerta* Wood, 1853, have been reported from Pleistocene deposits at Beauport in the Saint Lawrence River Valley, Miocene deposits in North Carolina and from the Corraline Crag of England (MacNeil, 1957).

Superfamily Carditacea Fleming, 1828

Family Carditidae Fleming, 1828

Subfamily Carditamerinae Chavan, 1969

Genus *Cyclocardia* Conrad, 1867

Subgenus *Cyclocardia, s.s.*

Cyclocardia (Cyclocardia) nuwokensis (Dall, 1920)

Plate III, Figures 3, 4

*Venericardia nuwok*ensis Dall, 1920: 33, pl. V, fig. 14

Cardita (Cyclocardia) nuwokensis (Dall) MacNeil, 1957: 105, pl. 12, fig. 22

Description – Shells small, thick, inflated, with prominent beaks; umbones slightly prosogyrate. Shell outline varies from sub-trigonal, with height exceeding length, to sub-orbicular. Sculpture of about 20 strong, radiating ribs with somewhat narrower

channeled interspaces, crossed by rather regularly spaced low threads which swell into nodules on the back of the ribs at their intersections. Base semicircular, internally crenulate in harmony with the external sculpture; hinge normal, teeth short and very strong for the size of the shell.

Material Examined – 8 specimens. 4 left valves: FAU726, height 6.56 mm, length 5.95 mm; FAU728, height 6.96 mm, length 6.53 mm; FAU731, height 7.44 mm, length 6.81 mm; FAU732, height 6.67 mm, length 6.25 mm. 4 right valves: FAU727, height 4.80 mm, length 4.65 mm; FAU729, height 4.29 mm, length 4.30 mm; FAU730, height 4.90 mm, length 4.82 mm; FAU733, height 4.27 mm, length 4.25 mm.

Type material – USNM 324310

Type locality – USGS Tertiary Location 7230, Carter Creek, a stream flowing into Camden Bay, Arctic Coast of Alaska

Stratigraphic occurrence – Oligocene, Nuwok Member of the Sagavanirktok Formation, Alaska

Distribution – Known only from the type locality

Discussion – Prior to the collection of these specimens this species was represented by the type and one other specimen, both poorly preserved. MacNeil (1957) compared *C. (Cyclocardia) nuwokensis* to *C. crebricostata* (Krause, 1885). However, the Carter Creek species has fewer ribs, is more trigonal in shape and is not compressed. It seems this species more closely resembles C. bailyi (Burch, 1944) from Monterey, California.

Cyclocardia (Cyclocardia) sp.

Plate III, Figures 5-9

Description – Shells thin, compressed, orbicular to subquadrate. Umbones not prominent, low, very slightly prosogyrate. Sculpture of about 23 strong, radiating ribs with narrow channeled interspaces, crossed by regularly spaced low threads which swell into nodules on the back of the ribs at their intersections. Internal ventral margin crenulate in harmony with external sculpture. Hinge normal; hinge teeth of average size for size of shell.

Material Examined – 6 specimens. 2 left valves: FAU719, height 11.61 mm, length 11.41 mm; FAU724, measurements indeterminate. 4 right valves: FAU720, height 5.23 mm, length 5.13 mm; FAU721, height 11.52 mm, length 11.37 mm; FAU723; FAU725, measurements indeterminate

Discussion – This species of *Cyclocardia (Cyclocardia)* has a very similar sculpture to that of *C. (Cyclocardia) nuwokensis*. However, they differ greatly in overall shape, shell thickness, umbone prominence and strength of hinge teeth. This species also seems to be on average slightly larger. There is some similarity to *C. barbarensis* (Stearns, 1890), known in Northern California from the Pliocene, but the Carter Creek form has a greater number of ribs that do not become obsolete near margins.

Superfamily Tellinacea Blainville, 1814

Family Tellinidae Blainville, 1814

Subfamily Macominae Olsson, 1961

Genus *Macoma* Leach, 1819

Macoma cf. calcarea(?) (Gmelin, 1791)

Plate IV, Figures 3,4

Tellina calcarea Gmelin, 1791: 3231

Tellina lata Gmelin, 1791: 3237

Tellina sabulosa Spengler, 1798: 114

Macoma tenera Leach, 1819: 465

Tellina sordida Couthouy, 1838: 59

Tellina proxima Sowerby in Gray and Sowerby, 1839: 154 *ex* Brown MS, non J. Smith, 1839

Tellina frigida Hanley, 1844: 143

Tellina lata nasuta Middendorf, 1849: 578, *non* T. nasuta Conrad 1837, a Macoma

Tellina dissimilis von Martens, 1865: 430, *non* Deshayes, 1855

Macoma sitkana Dall, 1900: 323

Macoma calcarea oblique Soot-Ryen, 1932: 36, *non* Tellina oblique Sowerby, 1817, a *Macoma*

Macoma calcarea longisinuata Soot-Ryen, 1932: 36

Macoma cf. calcarea (Gmelin), MacNeil, 1957: 106, pl. 12, fig. 11

Macoma calcarea sootryeni Petrov, 1966: 230, *ex* Scarlato MS

Abrina tatarica Scarlato, 1981: 373

Description – Shell is average size for genus, oval-elongate, somewhat compressed. Beaks are slightly twisted posteriorly, located 3/5 of the way toward posterior end.

Sculpture consists of fine to medium irregular, concentric threads. In all cases both valves are intact, held in place by carbonate matrix. Inner valves, including pallial sinus and teeth cannot be observed.

Material Examined – 4 well preserved specimens: FAU737, height 20.43mm, length 27.03mm; FAU 738, height 22.5mm, length 32.71mm; FAU739, height 20.81mm, length 28.94mm; FAU740, height 21.13mm, length 25.87

Stratigraphic Occurrence – Oligocene: Nuwok Member, North Slope, Alaska

Distribution – Recent species *Macoma calcarea* has circumarctic distribution ranging south to Denmark, Long Island, NY, Oregon and Japan (MacNeil, 1957; Abbott, 1974).

Discussion – Carter Creek *Macoma* is less inflated and has a less strong posterior twist than *M. calcarea*. Without observation of the diagnostic pallial sinus, the Carter Creek *Macoma* cannot be identified as *M. calcarea* with confidence. A *Macoma* was previously described from Carter Creek by Dall (1920) as a *Tellina*, but it appears to have been a *Macoma* with its ventral part missing. The origin of *Macoma calcarea* is uncertain due to questionable Tertiary records and age assignments, although it is regarded as having a Pacific origin (MacNeil, 1957). The genus dates back to Eocene time and *M. calcarea* is recorded from the Oligocene of Washington (Coan et al., 2000)

Superfamily Arcticacea Newton, 1891

Family Arcticidae Newton, 1891

Genus *Arctica* Schumacher, 1871

Arctica carteriana (Dall, 1920)

Plate IV, Figure 5

Astarte carteriana Dall, 1920: 31, pl. VI, figs. 1, 3

Arctica carteriana (Dall), MacNeil, 1957: 105, pl. 12, figs. 6, 8, 13-14, 23, 30

Description – Shell ovate, slightly elongate, rather inflated; sculpture consists of rude, incremental growth lines; anterior end shorter, beaks prosogyrate; there is no lunule or escutcheon; a rather long nymph supports a parivincular ligament posterior to the umbones; the ligament is preserved in several specimens; the nymph is visible in one specimen; the hinge of the right valve of one specimen is visible and contains two strong cardinal teeth and one posterior lateral tooth; the posterior end of the shell is bluntly rounded, the base evenly arcuate.

Material Examined – 12 specimens: FAU776, height 40.14 mm, length 48.38 mm; FAU767, height 39.64 mm, length 49.07 mm; FAU768-FAU777, all shells broken, measurements indeterminate. If specimens were complete the largest shell measurements would be approximately 60 mm high and 68 mm long; the smallest specimen would be approximately 24 mm high and 29 mm long.

Type material – USNM 324304

Type locality – USGS Station 7069, Carter Creek, a stream flowing into Camden Bay, Arctic Coast of Alaska

Stratigraphic Occurrence – Oligocene: Nuwok Member, North Slope, Alaska

Distribution – Known only from the type locality

Discussion – *Arctica ovata* (Meek and Hayden) is recorded from the Upper Cretaceous Bearpaw Shale of Montana. Post-Cretaceous, the only records of *Arctica* species are from the North Atlantic and Europe (Nicol, 1951) with living *Arctica* species having a northernmost limit of central Norway and northern Iceland (Marincovich et al., 1990). The presence of *Arctica* in the Late Oligocene Arctic is an indication of the possible Tertiary migration of the genus (MacNeil, 1957).

Order Myoida Stoliczka, 1870

Superfamily Hiatellacea Gray, 1824

Family Hiatellidae Gray, 1824

Genus *Cyrtodaria* Reuss, 1801

Cyrtodaria camdenensis Dall, 1920

Plate IV, Figures 6,7

Cyrtodaria camdenensis Dall, 1920: 33-34, pl. V, fig. 7; MacNeil, 1957: 107, pl. 11, figs. 21, 22, pl. 12, figs. 24, 25, 28

Original Description – Shell of moderate size, nearly equilateral, equivalve, gaping at both ends; the umbones subcentral, inconspicuous, the anterior end slightly longer; valves thick, with an unsculptured surface, more or less marked by concentric incremental lines; dorsal and ventral margins nearly parallel, anterior end rounded, posterior end subtruncate, rounded above and below; ligament strong and prominent; adductor scars

small, pallial line distinct, entire, with a small round scar at the ventral anterior end indicating the attachment of an area of the mantle; hinge edentulous; a small portion of the periostracum appears to be preserved and shows a black color.

Material Examined – 5 specimens: FAU778, height 16.61 mm, length 34.72 mm; FAU779, height 18.6 mm, length 40.11 mm; FAU780, height 15.1 mm, length 29.59 mm; FAU781, height 18.49 mm, length 39.14 mm; FAU782, height 18.06 mm, length 39.66 mm

Type material – USNM 324311

Type locality – USGS Station 7070, Carter Creek, a stream flowing into Camden Bay, Arctic Coast of Alaska

Stratigraphic occurrence – Oligocene: Nuwok Member, North Slope, Alaska

Distribution – genus comprise endemic atlantic bivalves (Dall, 1920 and Kauffman, 1967); Inner shelf habitat

Discussion – *Cyrtodaria* is a typical Arctic genus. There are two living boreal species of *Cyrtodaria*: the cirumarctic *C. kurriana* Dunker, 1861 and the Atlantic *C. siliqua* (Spengler, 1793). Coan et al. (2000) list *C. camdenensis* as a synonym for *C. kurriana*, but *C. camdenensis* is higher and, in some specimens, more elongate than a typical *C. kurriana* which rarely exceeds 40 mm. The ratio of length to height for *C. kurriana* is about 3; where as the average ratio of the *C. camdenesis* specimens is 2.11. The ratio of the shell's dimensions more closely resembles that of *C. siliqua*; however *C. siliqua* differs by having a more irregular pallial line and larger adductor scars. The specimens from Carter Creek show a definite twist to the right anteriorly. Coan et al. (2000)

indicate *C. kurriana* exhibits a similar twist while *C. siliqua* does not, while Abbott (1974) describes the opposite conditions for the two species. The specimens collected from Carter Creek seem to share an equal number of qualities with both living species and should therefore not be synonymized with *C. kurriana* at this time. Fossil *Cyrtodaria* species are known from Tertiary Europe, with no known occurrences in the Pacific region; an Atlantic origin is suggested for *C. camdenensis*.

Superfamily Pholadacea Lamarck, 1809

Family Pholadidae Lamarck, 1809

Subfamily Martesiinae Grant and Gale, 1931

Genus *Xylophaga* Turton, 1822

Xylophaga sp.

Plate IV, Figures 8, 9

Description – Shell globose, equivalve; anterior end shorter; posterior end set off by a deep radial sulcus; entire shell divided into three sculptural zones, two anterior to radial sulcus, the third begins at the anterior margin of the radial sulcus; anterior sculpture of evenly spaced, round topped, concentric ribs separated by slightly concave interspaces of the same thickness; medial sculpture of obliquely radial incised fine threads, regularly spaced, separated by flat, relatively wide interspaces; posterior sculpture of commarginal growth increments; shift between sculpture zones is abrupt, there is no transition zone.

Material Examined – 1 specimen: FAU783, length 12.23 mm

Discussion – The boreholes created in the wood by these organisms are filled with secondary crystalline calcite. As a result each shell is surrounded by a calcite mass, and in some cases the shell itself is recrystallized and can hardly be differentiated from the surrounding calcite. Only one specimen that could be considered sufficient to form the basis of a description could be removed from the calcite.

MacNeil (1957) reported a *Martesia* species from Carter Creek on the basis of crystallized borings; no shell was observed. However, based on shell shape, sculpture, size and the potential for the genus to be found in north boreal waters, it seems probable that the Carter Creek pholad belongs to the genus *Xylophaga*. This species size, shape and sculpture resemble that of *X. abyssorum* Dall, 1886 known as far north as New Jersey. There is a slight similarity to *X. washingtona* Bartsch, 1921 recorded as far north as Norton Sound in the Bering Sea. This species differs in being larger and having a more trigonal posterior. *X. dorsalis* is another form also known to range into north boreal waters.

5.2 Biogeography

The molluscan fauna from the Late Oligocene Nuwok Member bears a strong resemblance to modern Arctic-North Atlantic molluscan faunas, and is dramatically different from coeval Late Oligocene deposits worldwide. The Nuwok mollusks comprise the earliest known occurrence of such a modern Arctic looking fauna.

The similarity of the Nuwok fauna to modern Arctic-Atlantic taxa is striking. All but one genera, and possibly one species, still live in the Arctic Ocean or adjacent parts of

the high-latitude North Atlantic. The genus *Arctica*, for example, was previously known to have existed since the Cretaceous only in the North Atlantic, including the Baltic and Mediterranean Seas (MacNeil, 1957). *Palliolum groenlandica* is currently known only from the Atlantic.

The Nuwok molluscan fauna can only be compared with coeval faunas of the North Atlantic, since the Bering Strait was not open during the Late Oligocene (Marincovich and Gladenkov, 1999; Gladenkov *et al.*, 2002). The most similar coeval fauna appears to be from the Upper Oligocene-Lower Miocene Vejle Fjord Fm. in Denmark (I.K. Schnetler, Aarhus University, Denmark, pers. comm. to Marincovich, 2003). This fauna expectedly lived in warmer water, and is therefore more diverse than the Nuwok fauna (Schnetler and Beyer, 1987, 1990), although they appear to have formed in a similar shallow water, nearshore depositional environment. Extant cold water genera common to both faunas include the bivalves *Astarte, Cyclocardia, Nucula* and *Palliolum,* and the gastropods *Colus* and *Polinices.* The Nuwok fauna also has several genera in common with Oligocene mollusks from Kap Dalton and Kap Brewster in East Greenland (Hassan, 1953). These genera include the bivalves *Arctica, Astarte, Chlamys, Cyclocardia* and *Thyasira*, and the gastropod *Colus* and *Polinices*. The Nuwok molluscan fauna is less similar to the late Oligocene faunas of northern Germany, which are undoubtedly of a much warmer-water aspect (Janssen, 1978, 1979a, 1979b). There is no similarity between the Nuwok fauna and those of the Late Oligocene United States, from New Jersey to South Carolina, except for some shared cosmopolitan genera. Unlike

other Oligocene deposits, the Nuwok beds contain only one species, *Barbatia sp.*, which is a remnant of cosmopolitan Eocene faunas.

The presence of an *Antiplanes* species in the Nuwok is particularly puzzling because *Antiplanes* has long been considered to be exclusively Pacific in origin. At the time of deposition the Arctic had supposedly been isolated from the Pacific for over 70 million years, since the mid-Cretaceous. The remainder of the Nuwok fauna does not bear a resemblance to fossil Pacific assemblages. For example, there is very little similarity to Miocene faunas from the Gulf of Alaska region, such as that from the Yakataga Fm. on the south coast of Alaska and the Unga Fm. (late Miocene) of the Alaska Peninsula region (MacNeil, 1957). All other lines of evidence suggest that there were not any connections between the Arctic and the Pacific Oceans at the time of deposition of the Nuwok sediments. However, the Nuwok *Antiplanes* may indicate that some form of connection, perhaps intermittent, existed during the Late Oligocene.

CHAPTER 6

6.0 Conclusions

6.1 Paleoclimate of the late Oligocene Arctic Ocean

Paleotemperatures derived from isotopic study of molluscs from the Nuwok Member type locality at Carter Creek indicate substantial cooling during the late Oligocene. Paleotemperature data strongly imply that the Arctic Ocean became colder much earlier than previously thought. The characteristically cold-water biota of the Nuwok Member supports the notion of a relatively cold Arctic Ocean marine climate in the late Oligocene.

The late Oligocene Arctic Ocean was only slightly warmer than the modern Beaufort Sea, where summer temperatures rarely go above +2°C and winter temperatures are roughly -1°C (Levitus *et al.*, 1994). Isotopically derived paleotemperatures indicate the Late Oligocene Arctic Ocean was significantly colder than most Paleogene oceans. For example, the average paleotemperatures range for the late Oligocene North Sea (52 to 55°N) was 10.0 to 12.9 °C, with a potential error of ±4°C (Buchardt, 1978). There are no late Oligocene isotopic data from the U.S. Gulf Coast (paleolatitude 30°N). However, early Oligocene isotopic paleotemperatures calculated from molluscs yield average annual temperatures of 22 to 23°C (Kobashi, *et al.*, 2001). Seasonal fluctuations from ~20°C in summer to as low as 11.0°C in winter have been inferred from Gulf Coast fish otoliths (Ivany, *et al.*, 2000). Early to late Oligocene paleotemperatures in the North

Pacific, based on $\delta^{18}O$ from the bivalve *Cyclocardia*, were 3 to 5°C at a paleodepth of 400 m, which implies that Oligocene surface-water conditions at 60°N were similar to those between 40 and 45°N today (Oleinik, 1993).

6.2 Evolution and Diversification of Late Oligocene Arctic Biota

The Late Oligocene Arctic Ocean appears to have been a significant center of evolution for modern Arctic taxa. The biota of the Nuwok Member also implies that a relatively cold Arctic Ocean marine climate prevailed in the late Oligocene and has persisted to the present. As a result of dwelling in a continuously cold ocean, Arctic molluscs have not evolved as fast or as profoundly, from the late Oligocene to the Holocene, as have molluscs elsewhere in the world that had to adapt to fluctuating climates. The presence of modern-looking molluscs coincident with characteristically, late Oligocene benthic foraminifera and supporting Sr age data implies heterochroniety, at least for Arctic shelf biotas, and implies different rates of evolution between these invertebrate groups.

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APPENDIX 1

SYSTEMATIC PLATES I - IV

PLATE I

Figures 1, 2. *Frigidoalvania cartercreekensis, n.sp.*
FAU 700, height 3.60 mm, width 2.00 mm.

3, 4. *Polinices (Euspira) pallidus* (Broderip and Sowerby, 1829).
FAU705, height 6.32 mm, width 6.04 mm.

5, 6. *Choristes cf. carpenteri* (Dall, 1896).
FAU704, height 6.65 mm, width 5.31 mm.

7, 8. *Aulacofusus sp.*
FAU711, height 24.24 mm, width 12.63 mm.

9, 10. *Antiplanes(?) sp.*
FAU703, height 17.25 mm, width 6.46 mm.

11, 12. *Scaphander aff. Lignarius (Linné*, 1758).
FAU734, height 31.85mm, width 18.83mm.

13. *Cadulus arcticus* Dall, 1920.
FAU745, length 5.64mm.

PLATE I

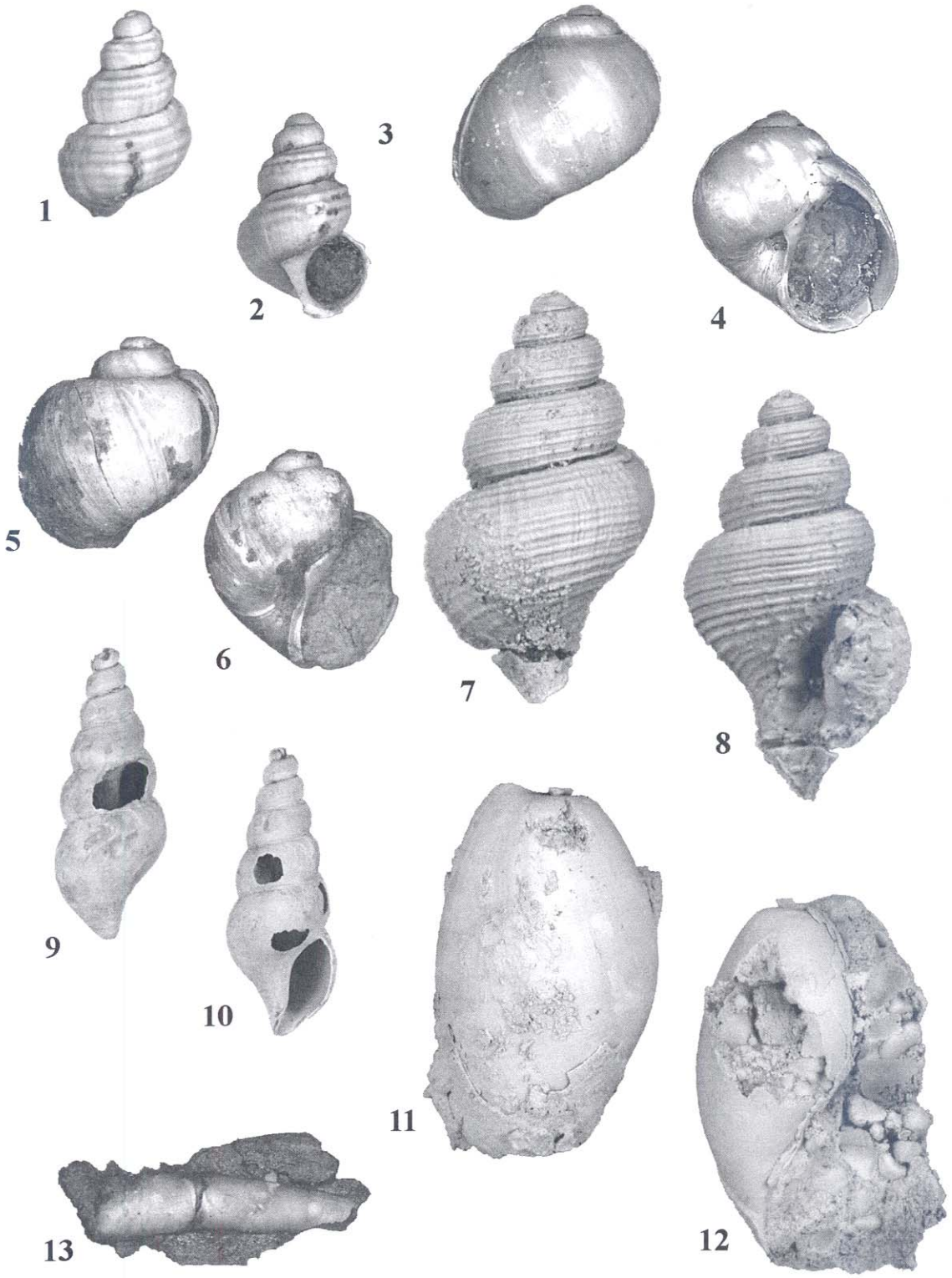


PLATE II

Figures 1. *Nucula sp.*

FAU 747, portion of hinge, length 6.13 mm.

2. *Nuculana morrisi* MacNeil, 1957.

FAU742, left valve, height 11.41 mm, length 19.63 mm.

3. *Solemya sp.*

FAU752, height indeterminate, length 64.4 mm.

4, 5. *Barbatia (Barbatia)(?) sp.*

4. FAU753, left valve, height 5.33 mm, length 9.74 mm.

5. FAU754, left valve, height 3.36 mm, length 6.23 mm.

6, 7. *Bathyarca sp.*

6. FAU756, left valve, height 3.59 mm, length 4.75 mm.

7. FAU756, right valve, height 3.59 mm, length 4.75 mm.

8, 9. *Limopsis aff. panamensis* Dall, 1902.

8, 9. FAU710, left valve, height 5.32 mm, length 5.61 mm.

10 - 13. *Chlamys nuwokensis* MacNeil, 1957.

10, 11. FAU757, right valve, height 36 mm, length 39.82 mm.

12, 13. FAU758, left valve, height 25.87 mm, length 32.38 mm.

14, 15. *Palliolum groenlandicum* (Sowerby)

14. FAU759, right valve, height 8.11 mm,length 8.02 mm.

15. FAU759, left valve, height 8.11 mm,length 8.02 mm.

PLATE II

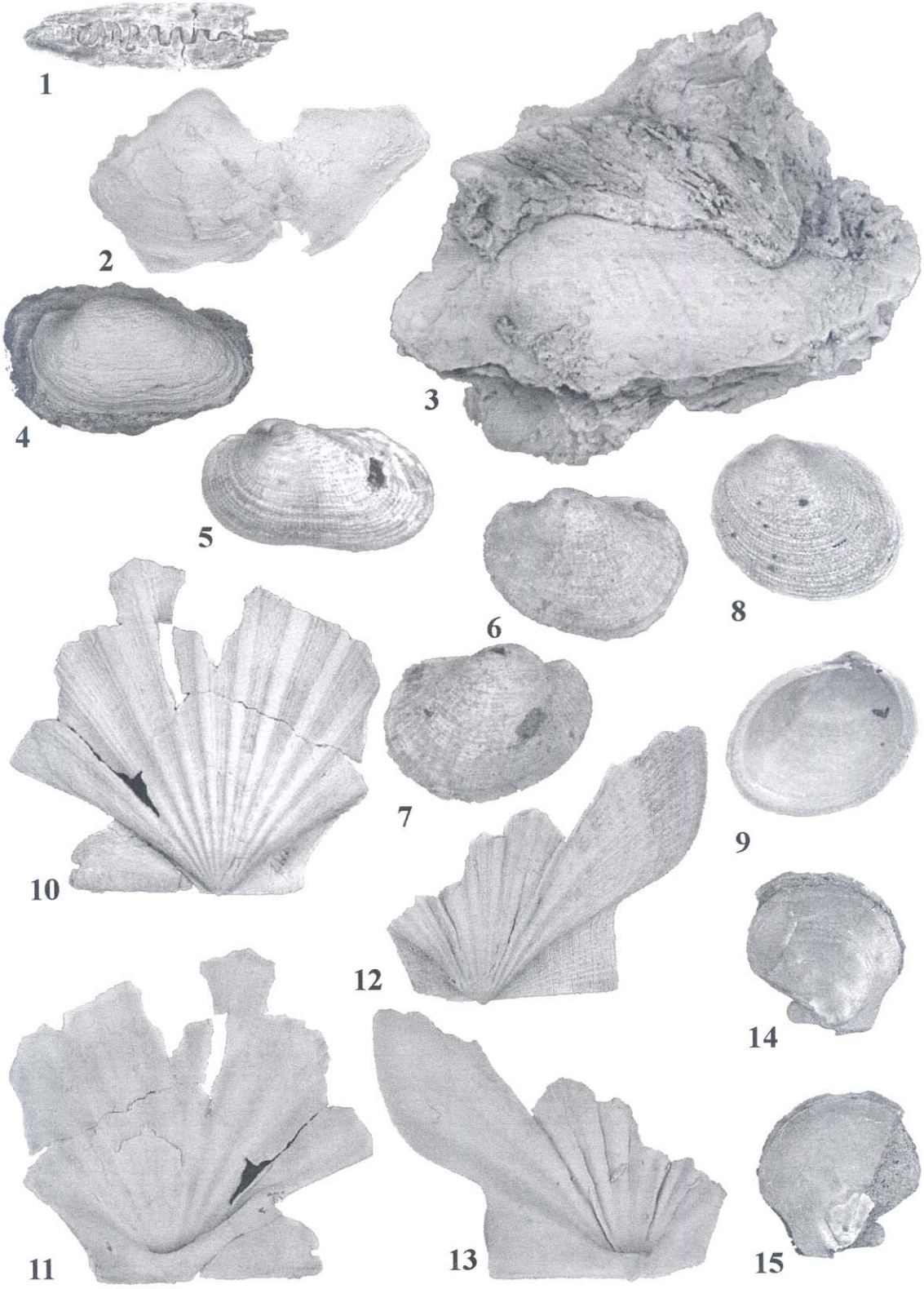


PLATE III

Figures 1, 2. *Thyasira alaskana* (Kaufman, 1969).

1. FAU762, right valve, height 25.9 mm, length 25.53 mm.

2. FAU764, left valve, height 34.92 mm, length 34.51 mm.

3, 4. *Cyclocardia (Cyclocardia) nuwokensis* (Dall, 1920).

FAU726, left valve, height 6.56 mm, length 5.95 mm.

5 - 9. *Cyclocardia (Cyclocardia) sp.*

5, 6. FAU720, right valve, height 5.23 mm, length 5.13 mm.

7, 8. FAU719, left valve, height 11.61 mm, length 11.41 mm.

9. FAU721, right valve, height 11.52 mm, length 11.37 mm.

PLATE III

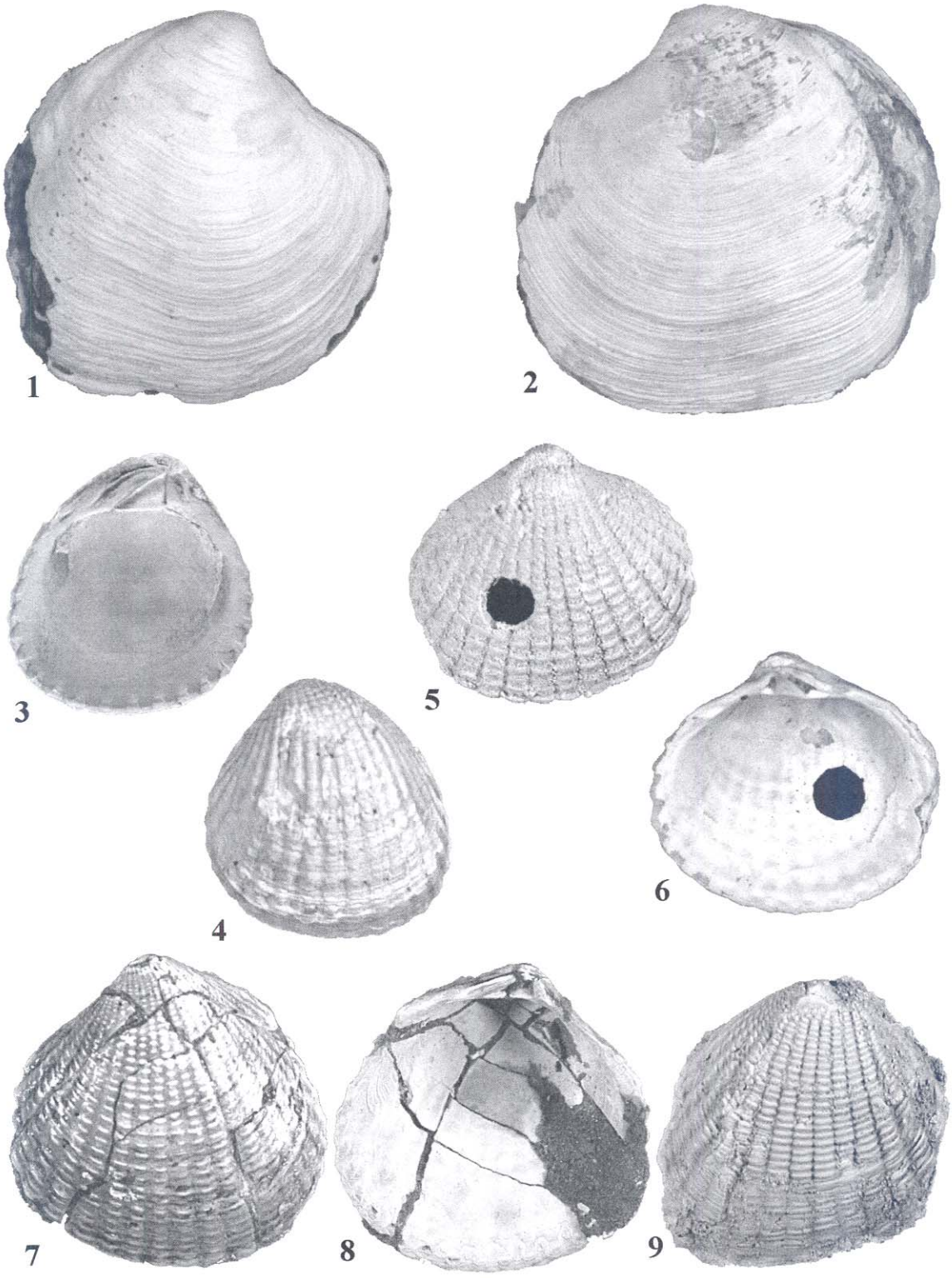


PLATE IV

Figures 1, 2. *Astarte martini* Dall, 1920.

FAU784, right valve, height 14.59 mm, length 17.68 mm.

3, 4. *Macoma cf. calcarea(?)* (Gmelin, 1791).

3. FAU737, right valve, height 20.43mm, length 27.03mm.

4. FAU737, left valve, height 20.43mm, length 27.03mm.

5. *Arctica carteriana* (Dall, 1920).

FAU776, right valve, height 40.14 mm, length 48.38 mm.

6, 7. *Cyrtodaria camdenensis* Dall, 1920.

6. FAU778, left valve, height 16.61 mm, length 34.72 mm.

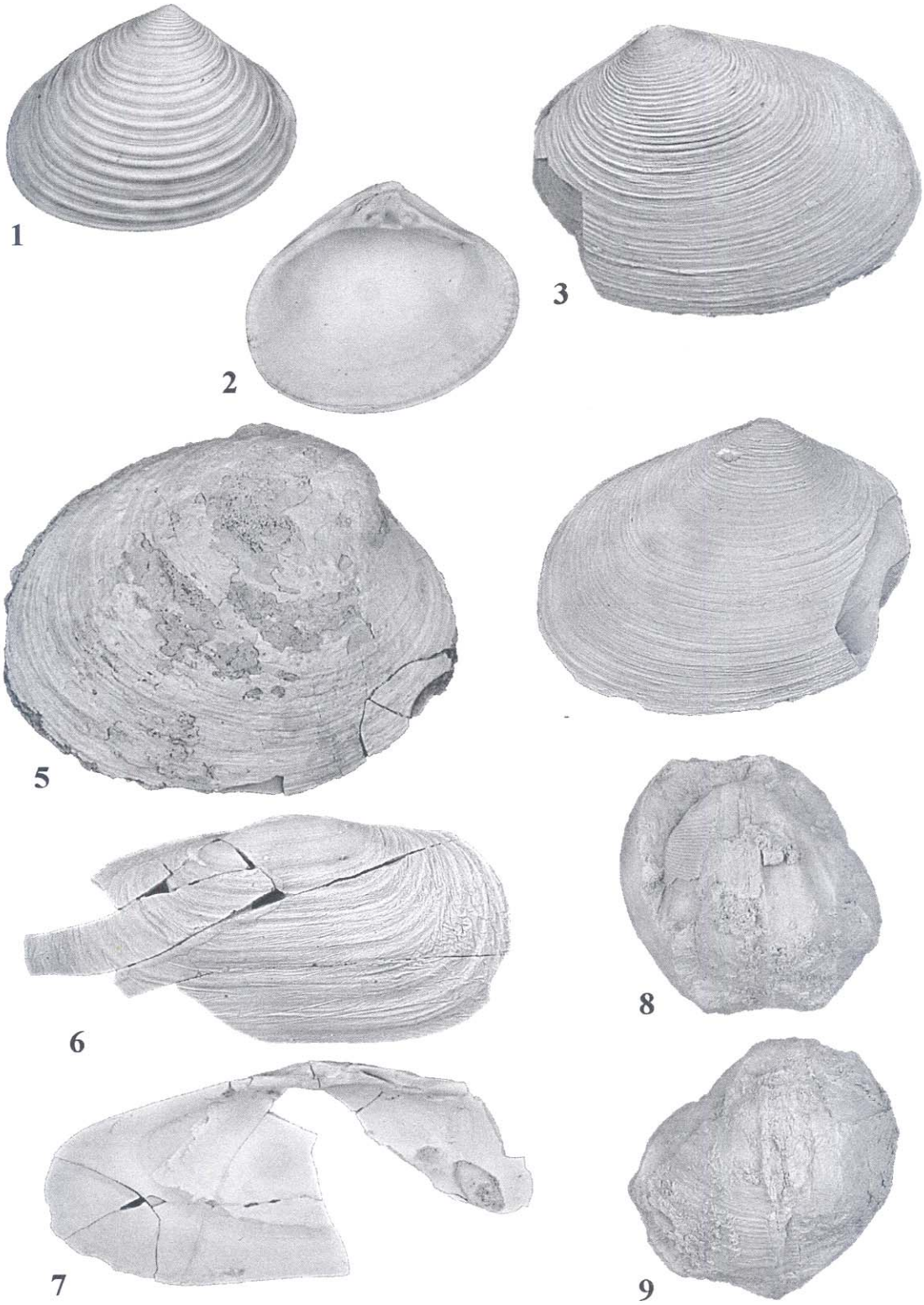
7. FAU782, right valve, height 18.06 mm, length 39.66 mm.

8, 9. *Xylophaga sp.*

8. FAU783, left valve, height 10.07 mm, length 12.23 mm.

9. FAU783, right valve, height 10.07 mm, length 12.23 mm.

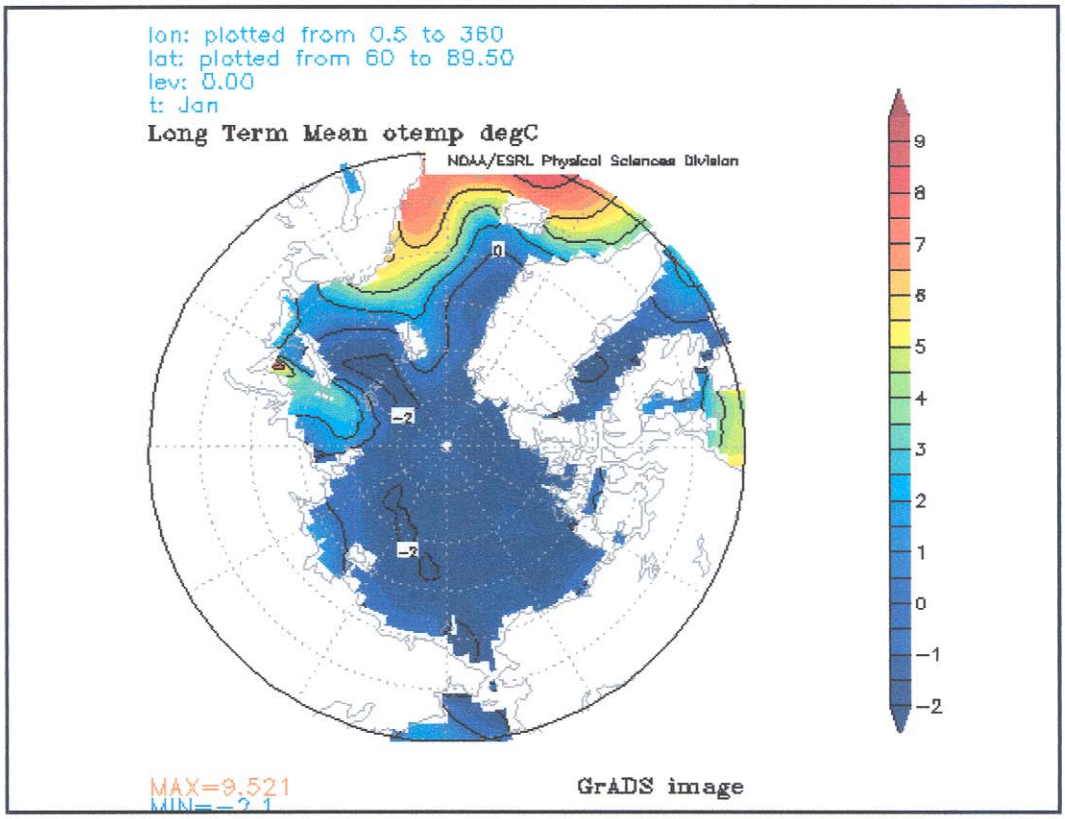
PLATE IV

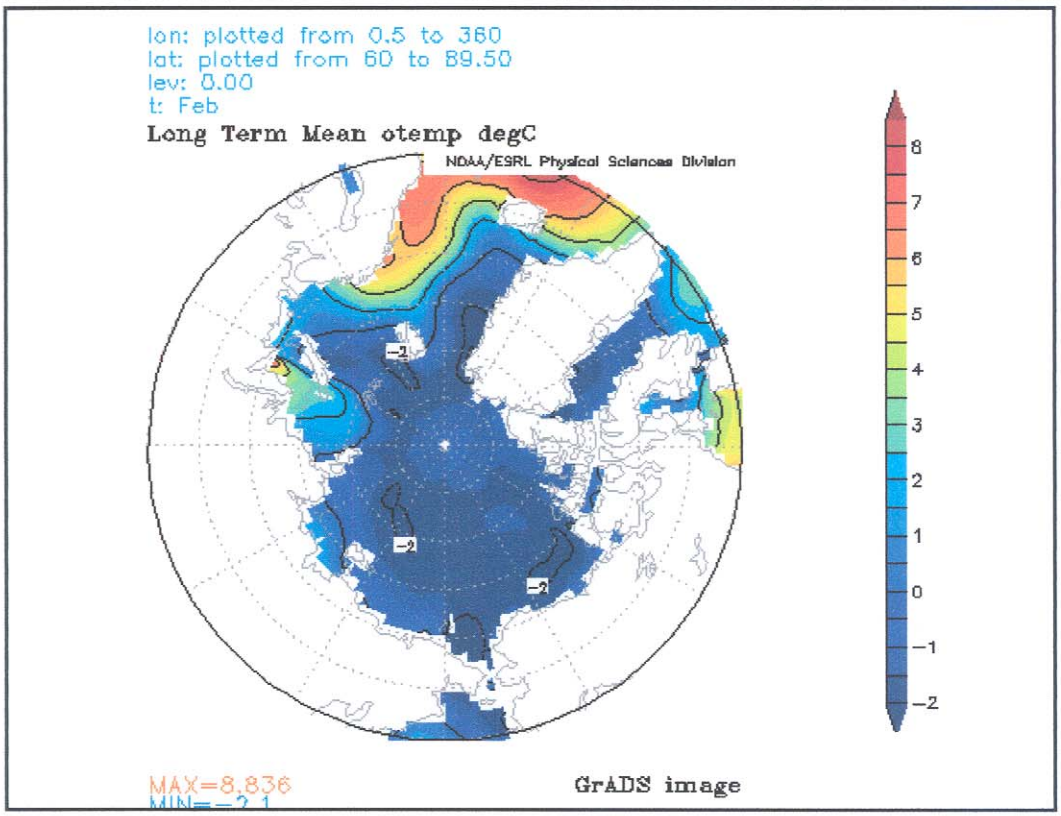


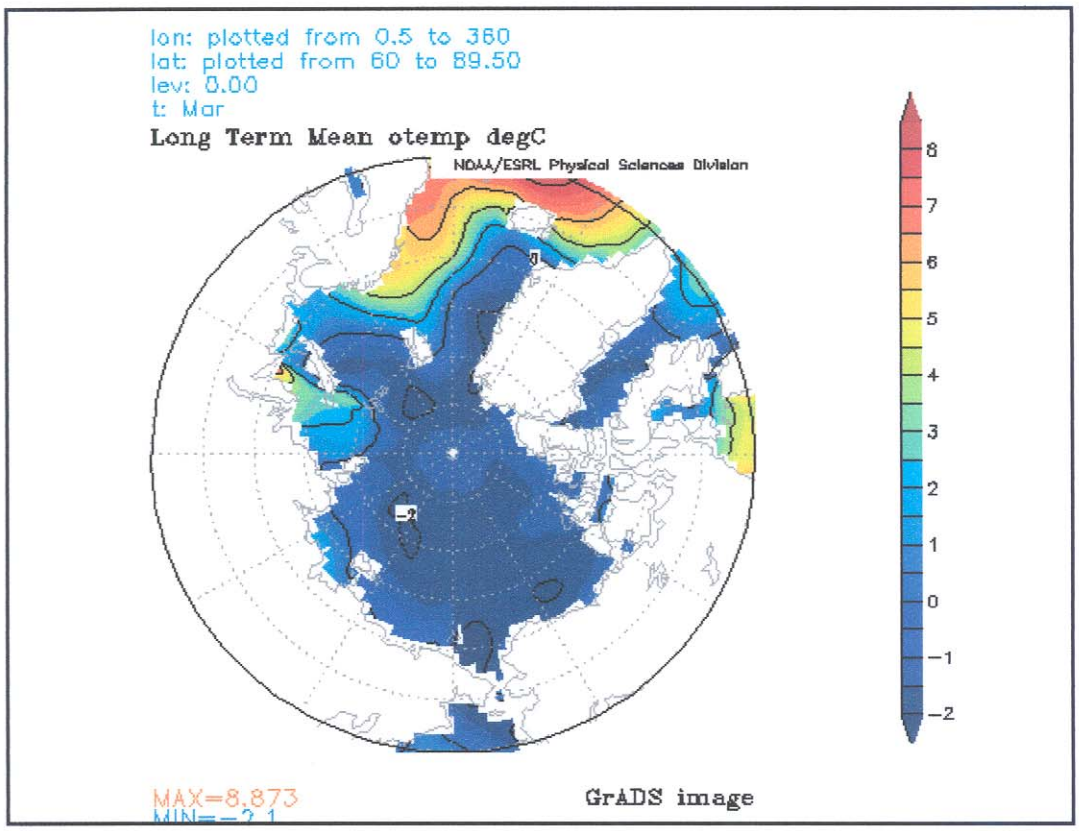
APPENDIX 2

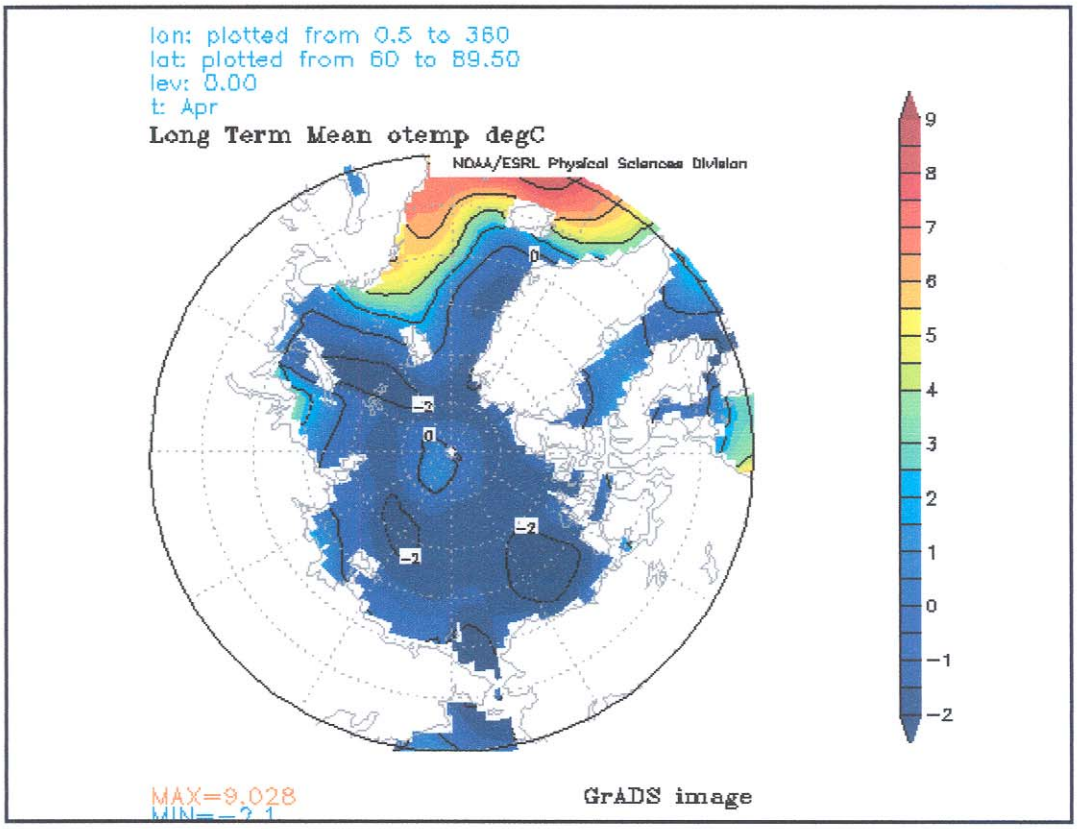
Monthly Isothermal Maps:
Arctic Ocean, Chukchi Sea, Iceland and Washington
(Levitus) World Ocean Atlas, 1994

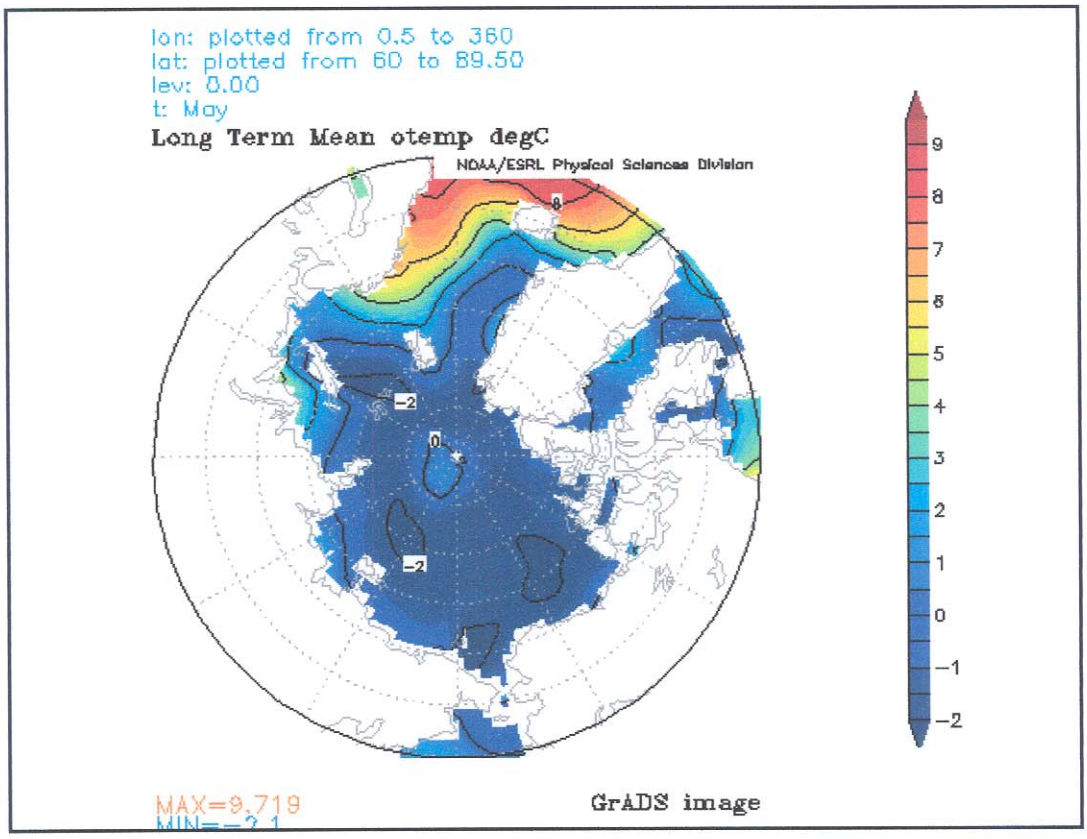
Monthly Isothermal Maps: Arctic Ocean
(Levitus) World Ocean Atlas, 1994

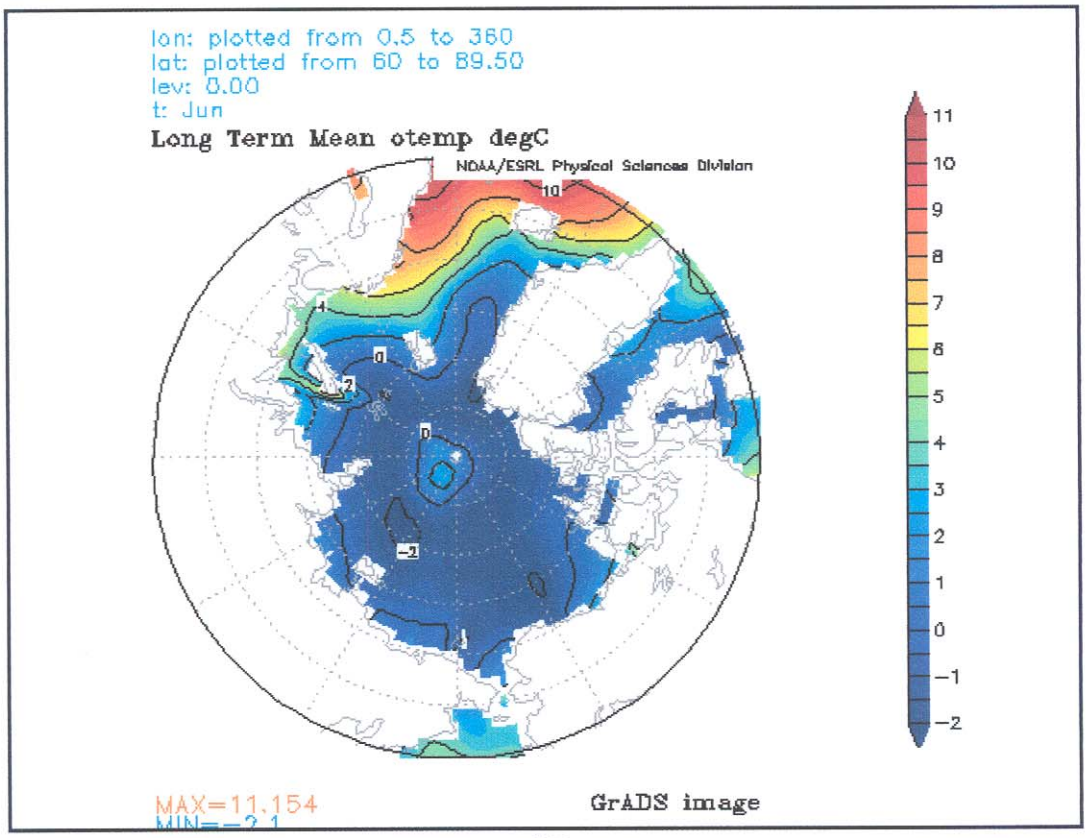

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Jan
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=9.521
GrADS image

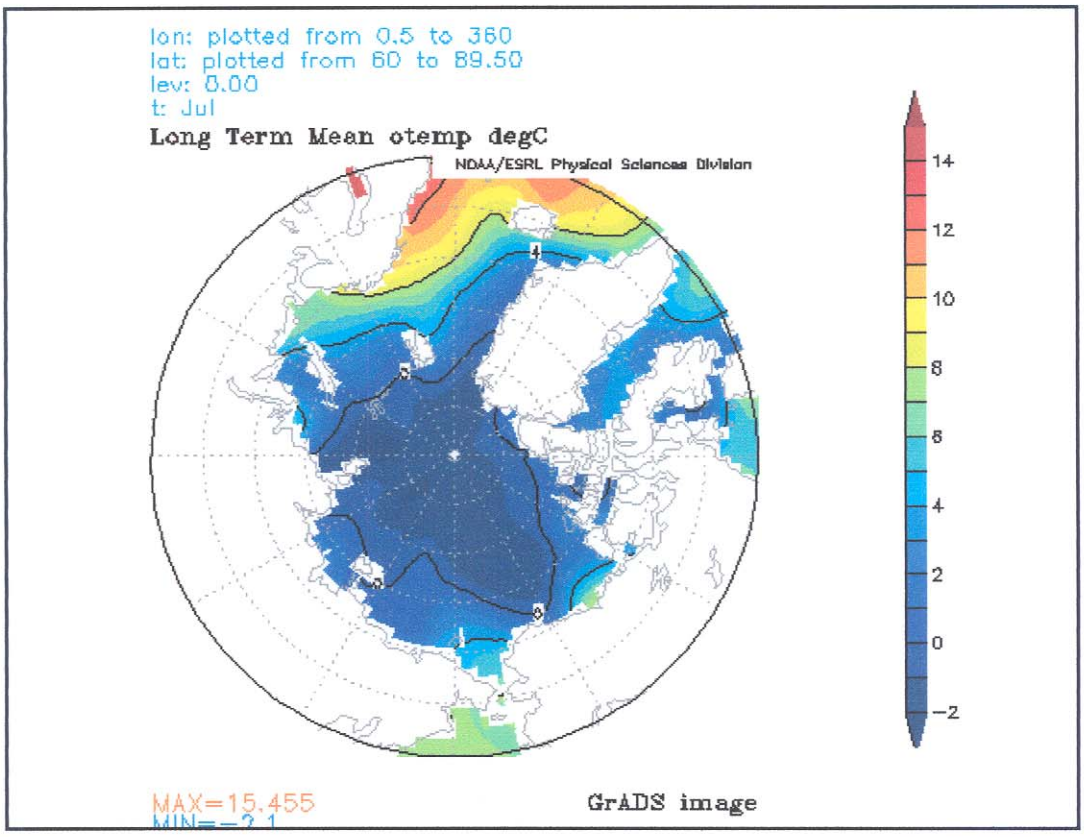

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Feb
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
8
7
6
5
4
3
2
1
0
−1
−2
MAX=8.836
GrADS image

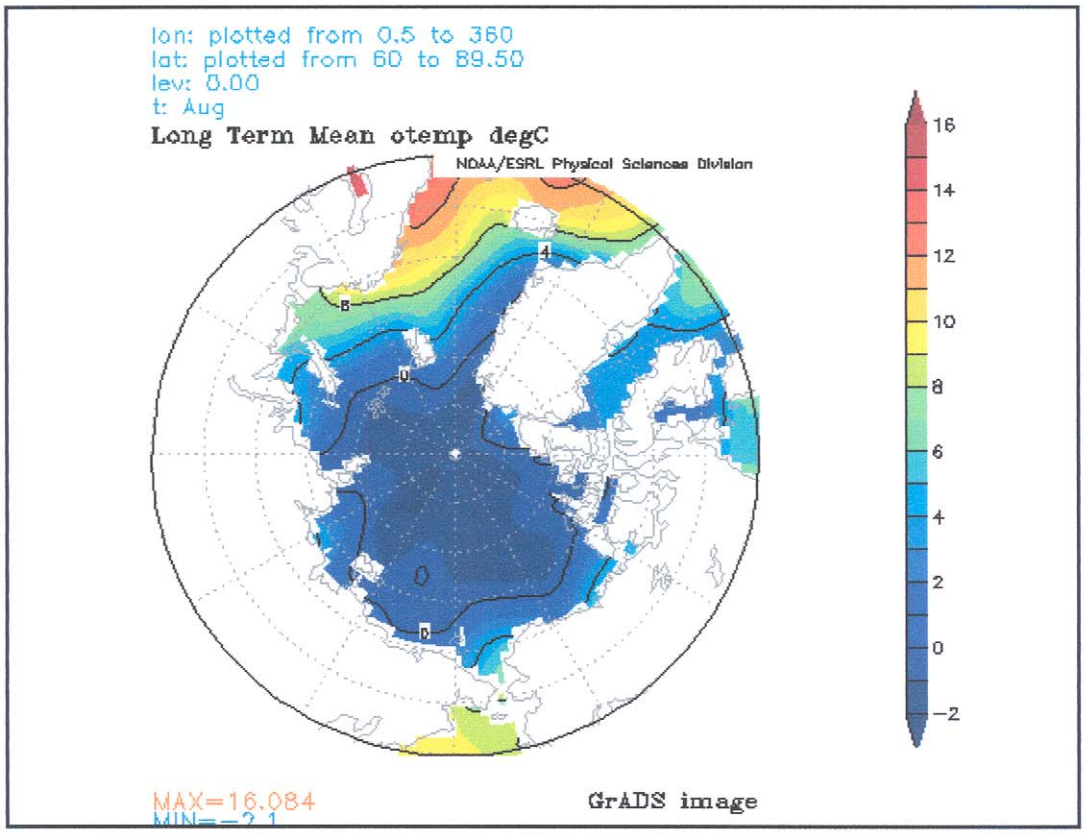

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Mar
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
8
7
6
5
4
3
2
1
0
−1
−2
MAX=8.873
GrADS image

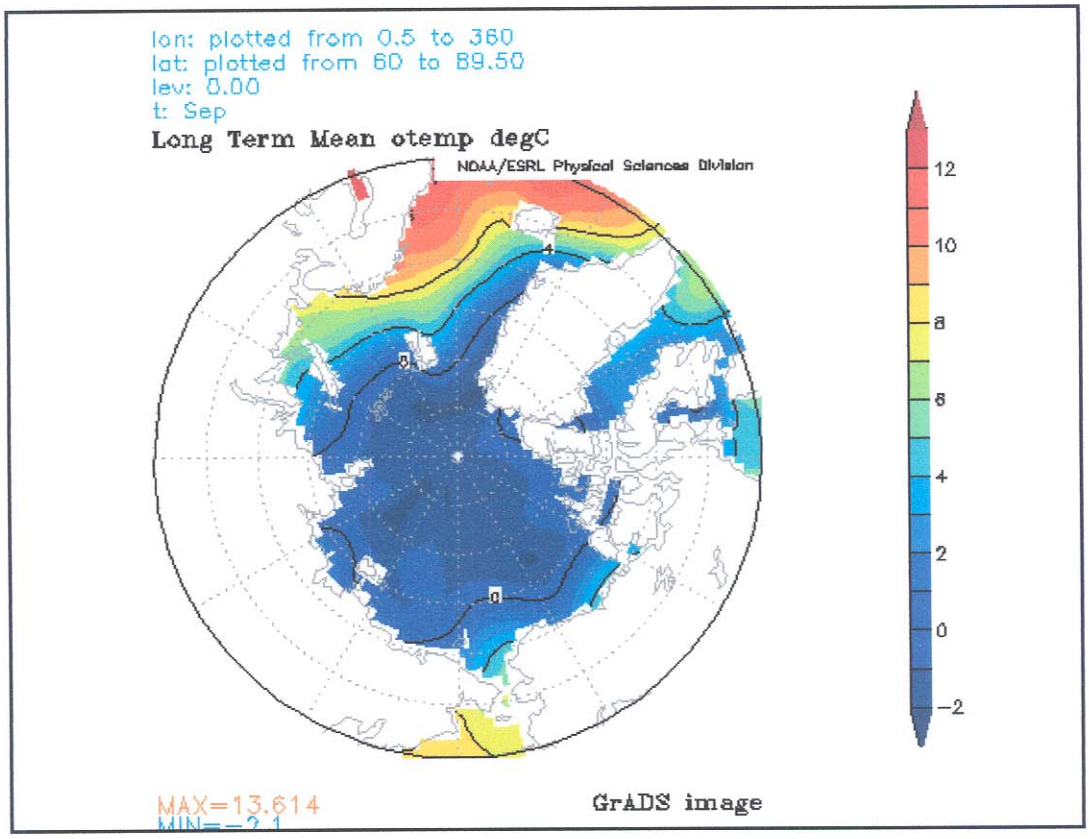

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Apr
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=9.028
GrADS image

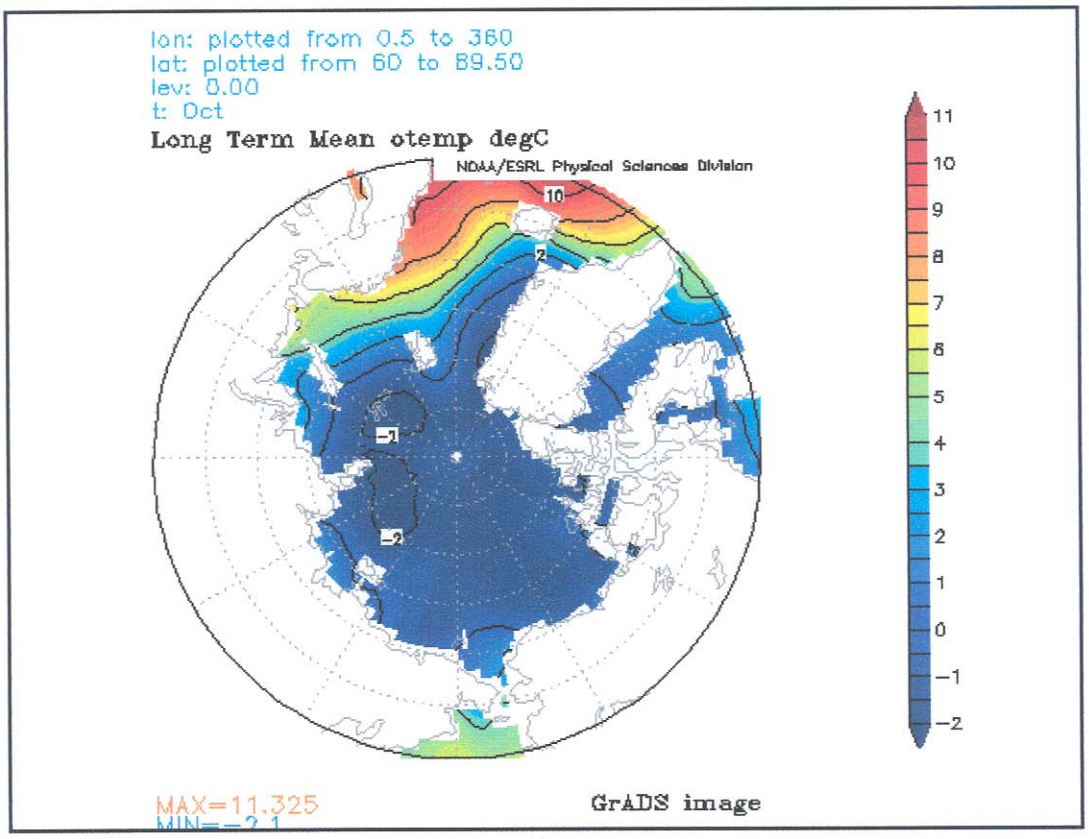

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: May
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=9.719
GrADS image

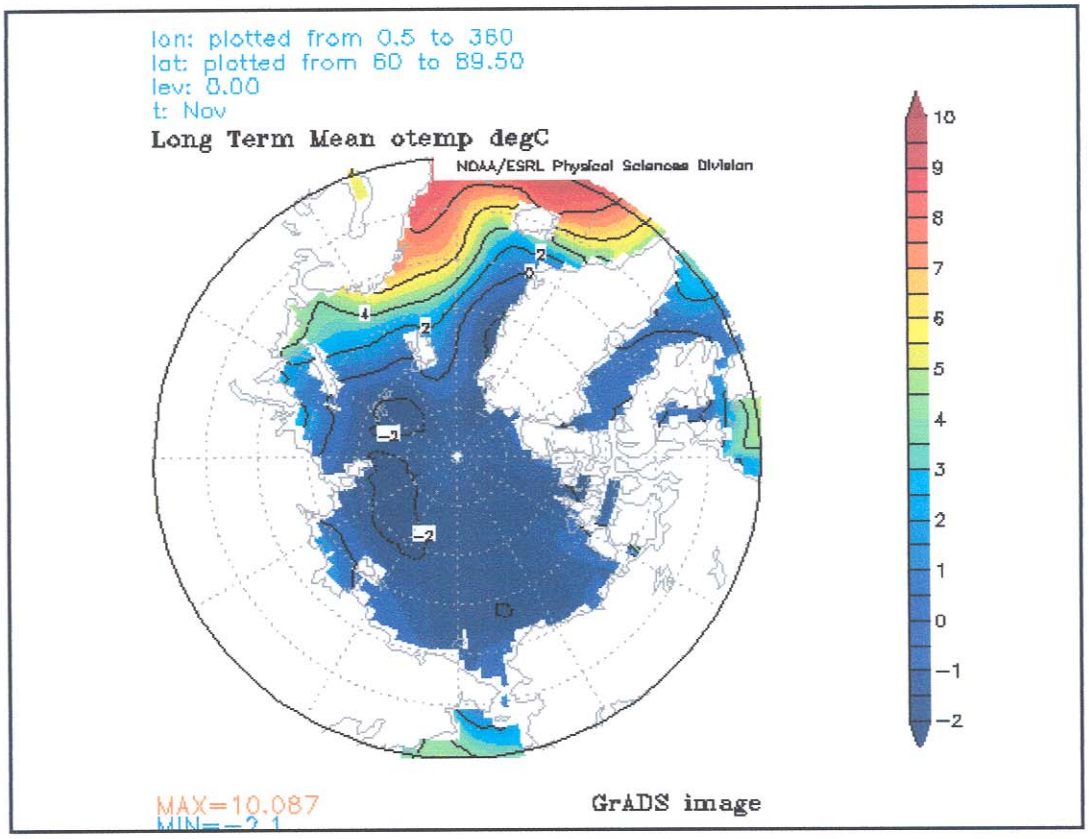

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Jun
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
11
10
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=11.154
GrADS image

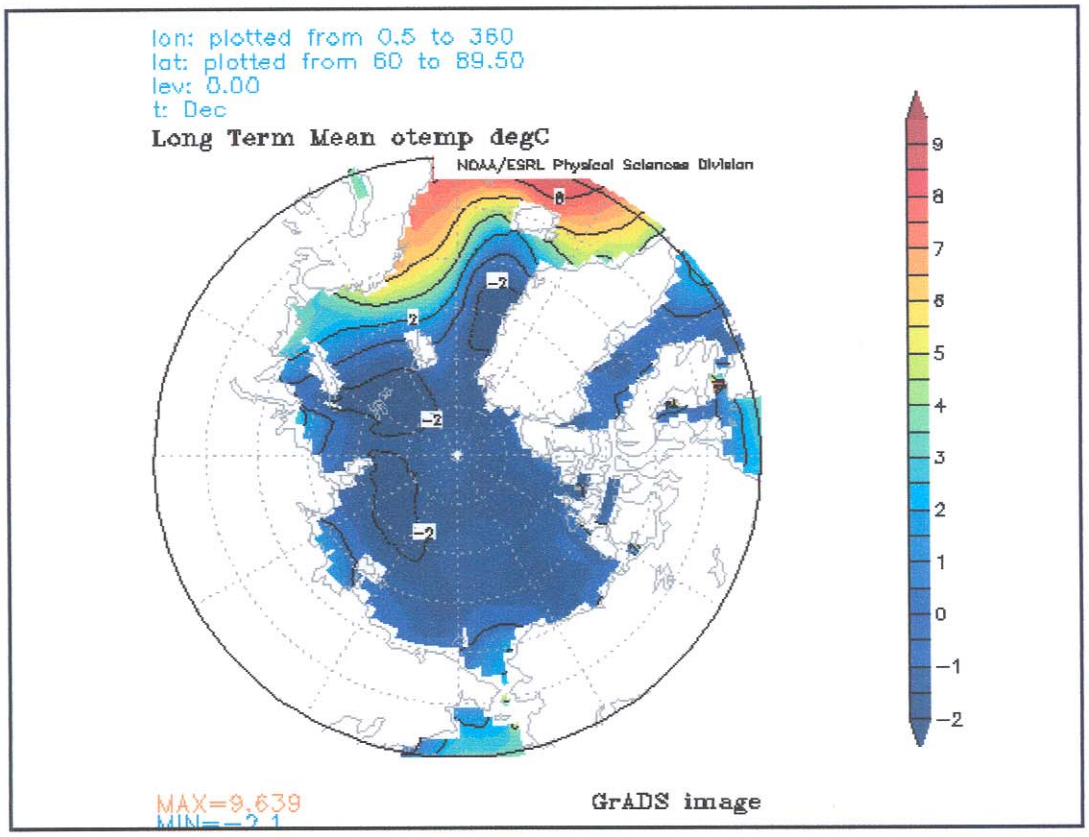

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Jul
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
14
12
10
8
6
4
2
0
−2
MAX=15.455
GrADS image


lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Aug
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
16
14
12
10
8
6
4
2
0
−2
MAX=16.084
GrADS image

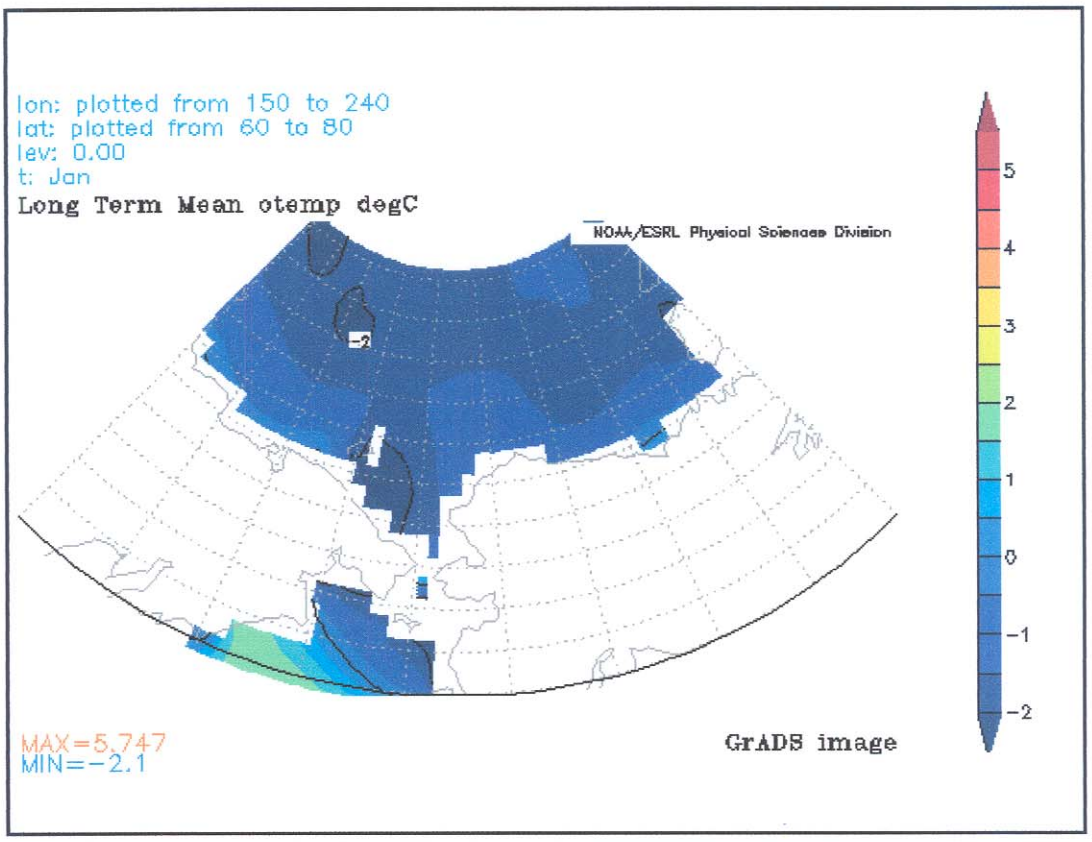

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Sep
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
12
10
8
6
4
2
0
−2
MAX=13.614
GrADS image

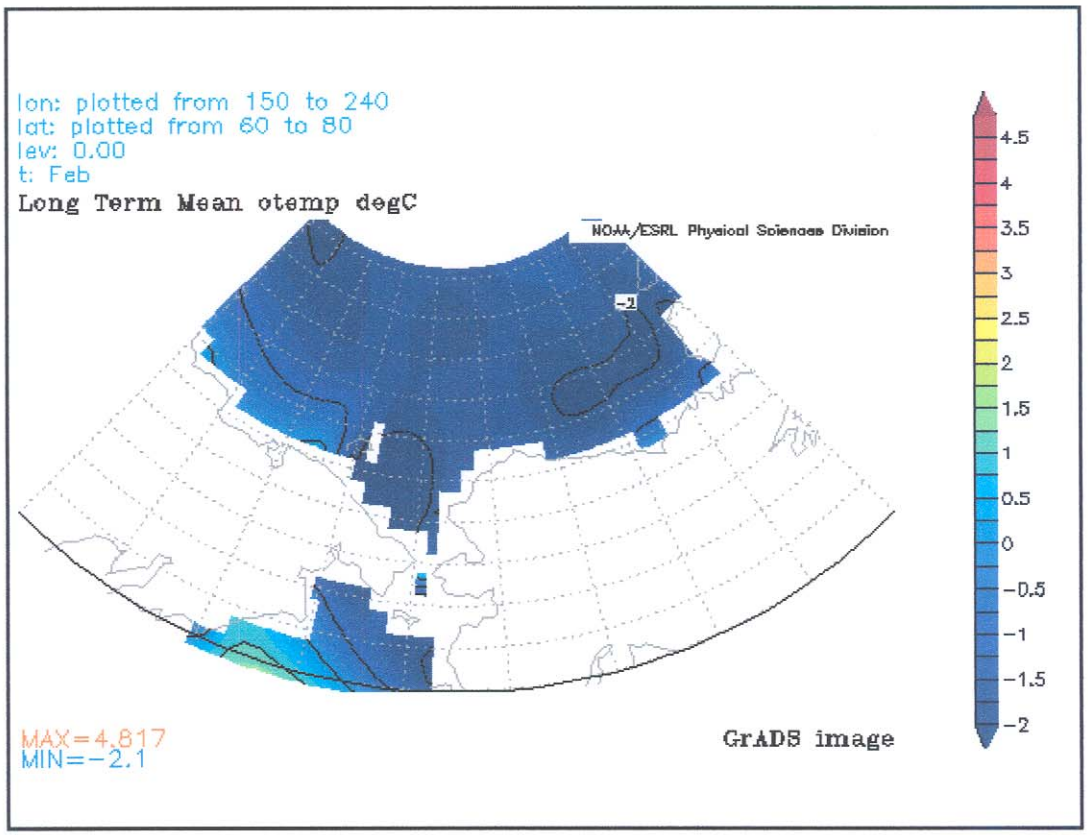

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Oct
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
11
10
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=11.325
GrADS image

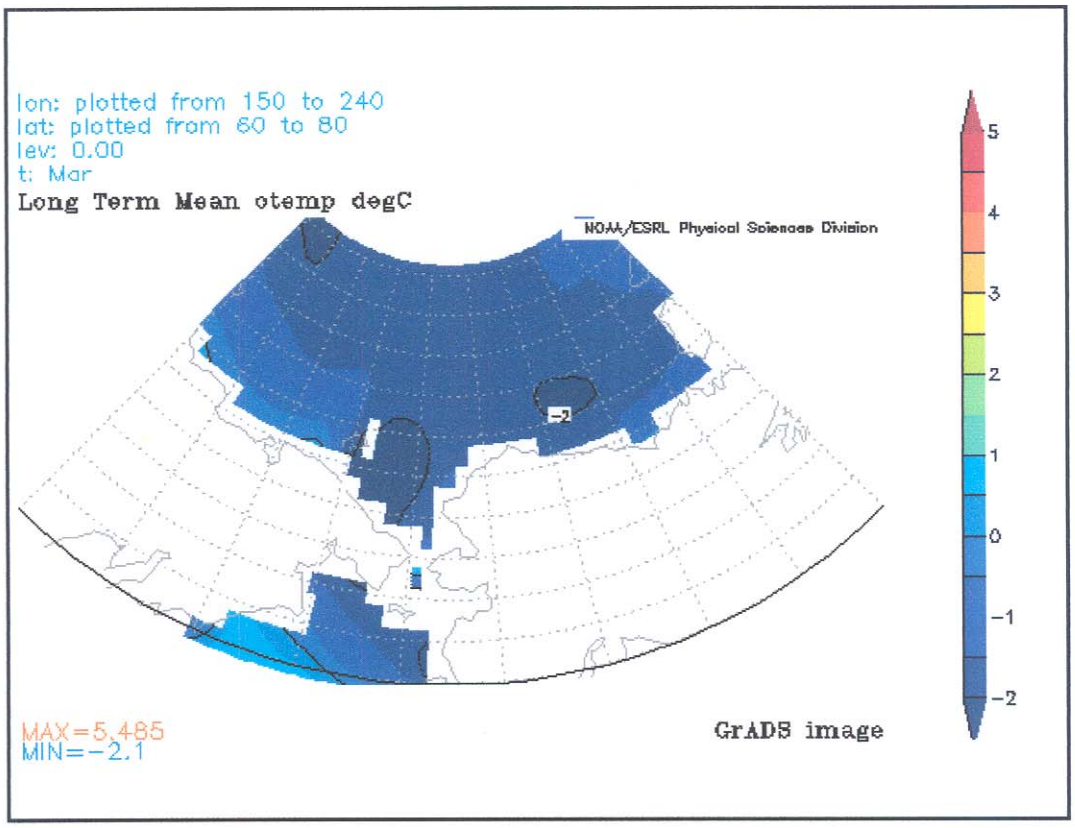

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Nov
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
10
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=10.087
GrADS image

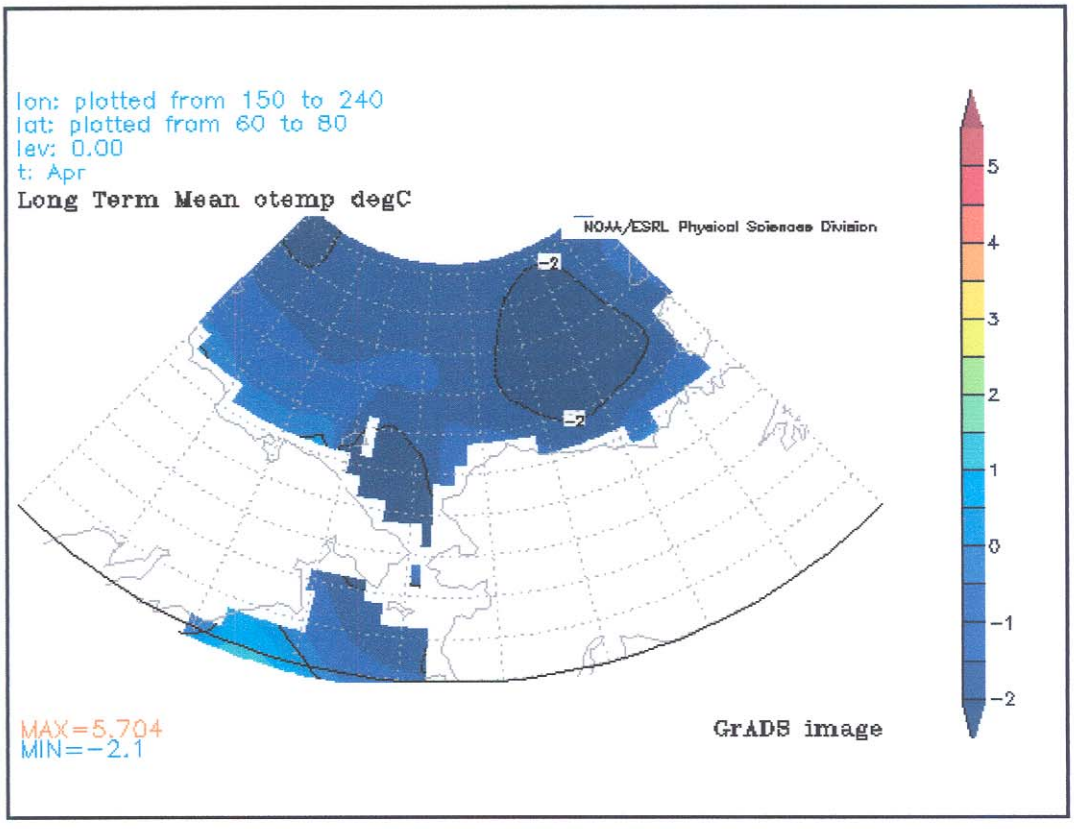

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Dec
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=9.639
GrADS image

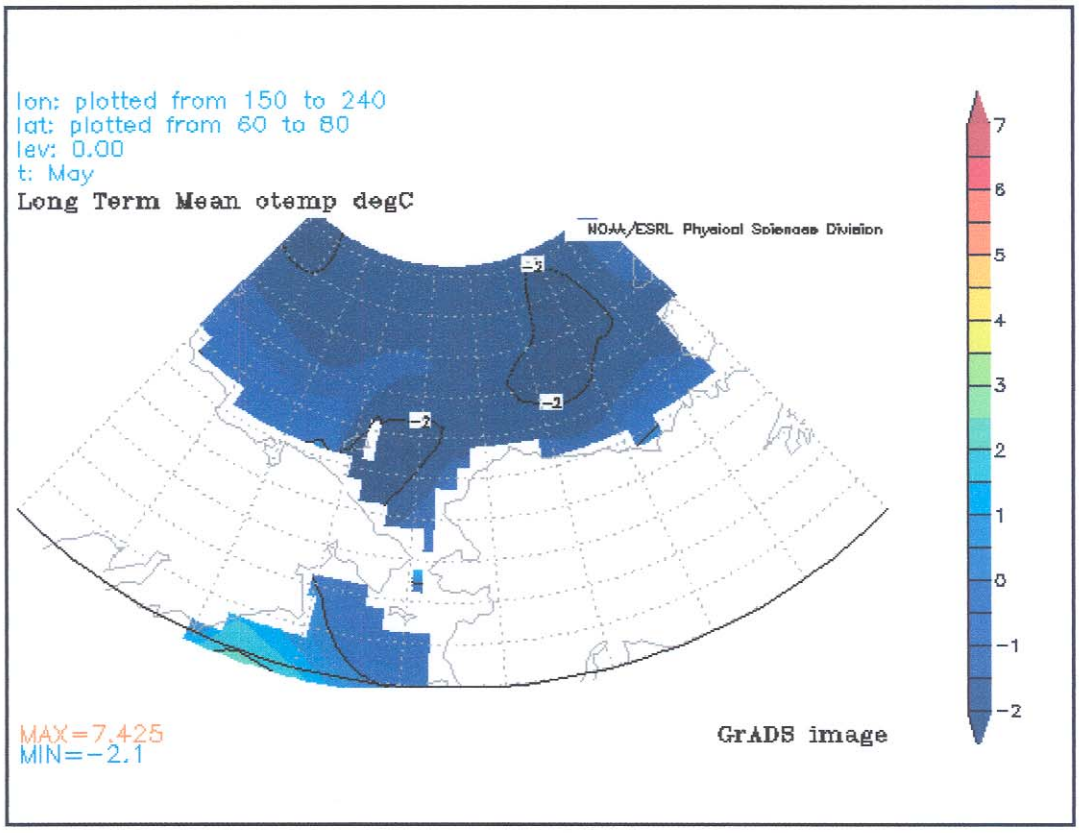
Monthly Isothermal Maps: Chukchi Sea
(Levitus) World Ocean Atlas, 1994

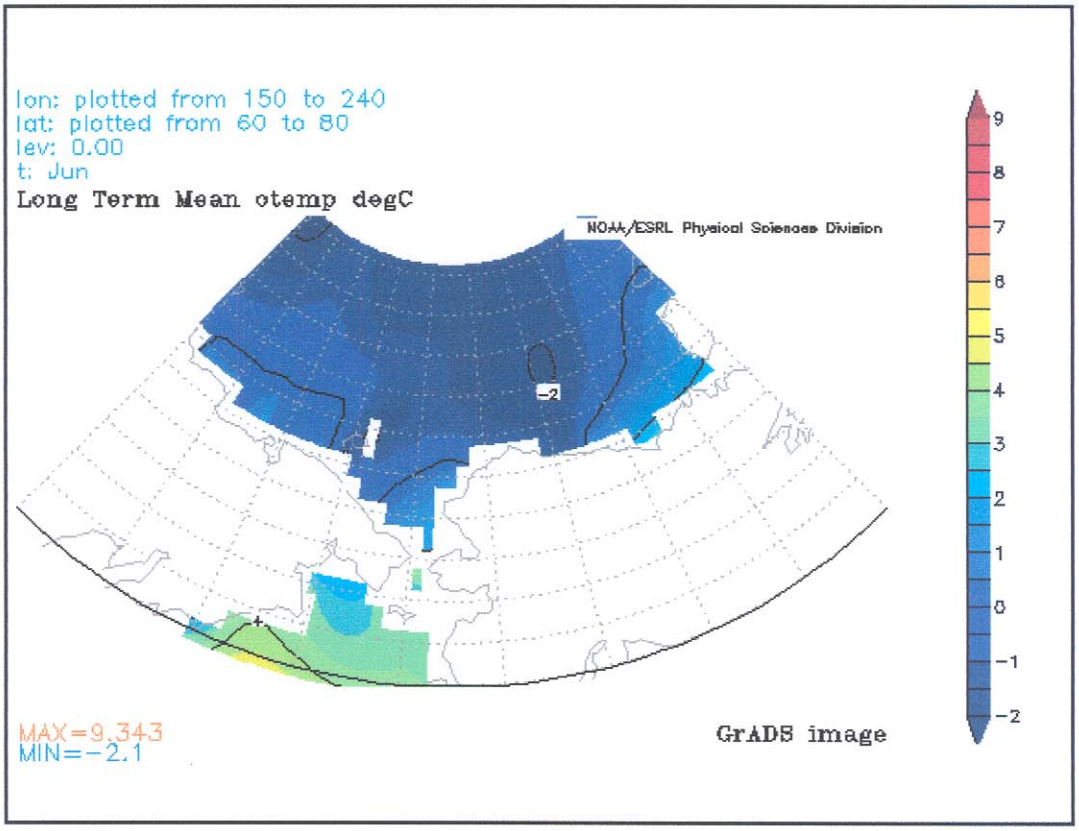

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Jan
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
-2
5
4
3
2
1
0
-1
-2
MAX=5.747
MIN=-2.1
GrADS image

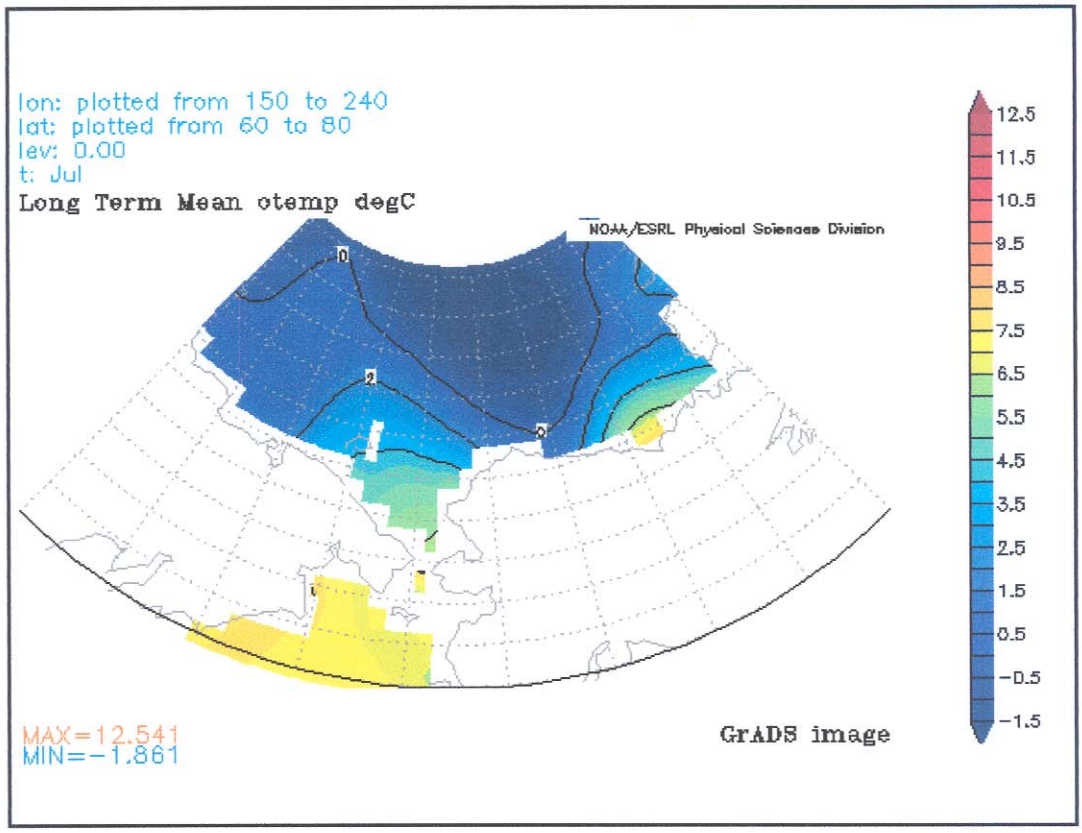

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Feb
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
-2
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
MAX=4.817
MIN=-2.1
GrADS image

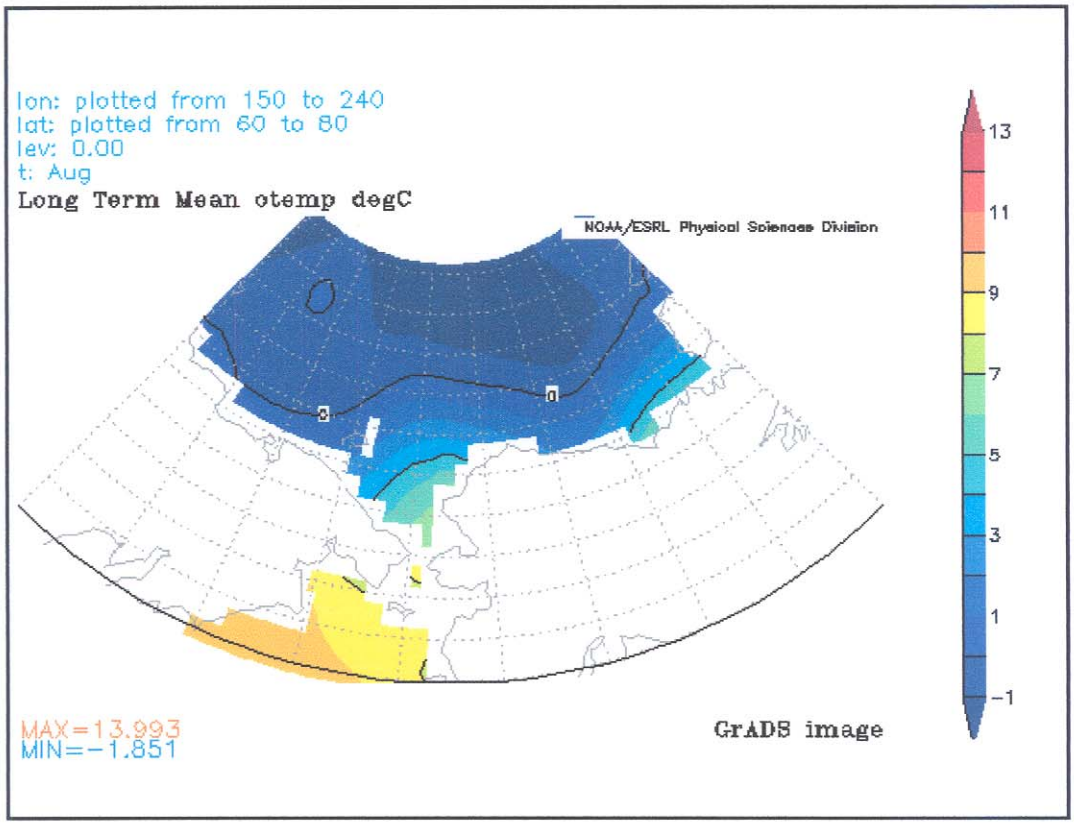

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Mar
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
-2
5
4
3
2
1
0
-1
-2
MAX=5.485
MIN=-2.1
GrADS image

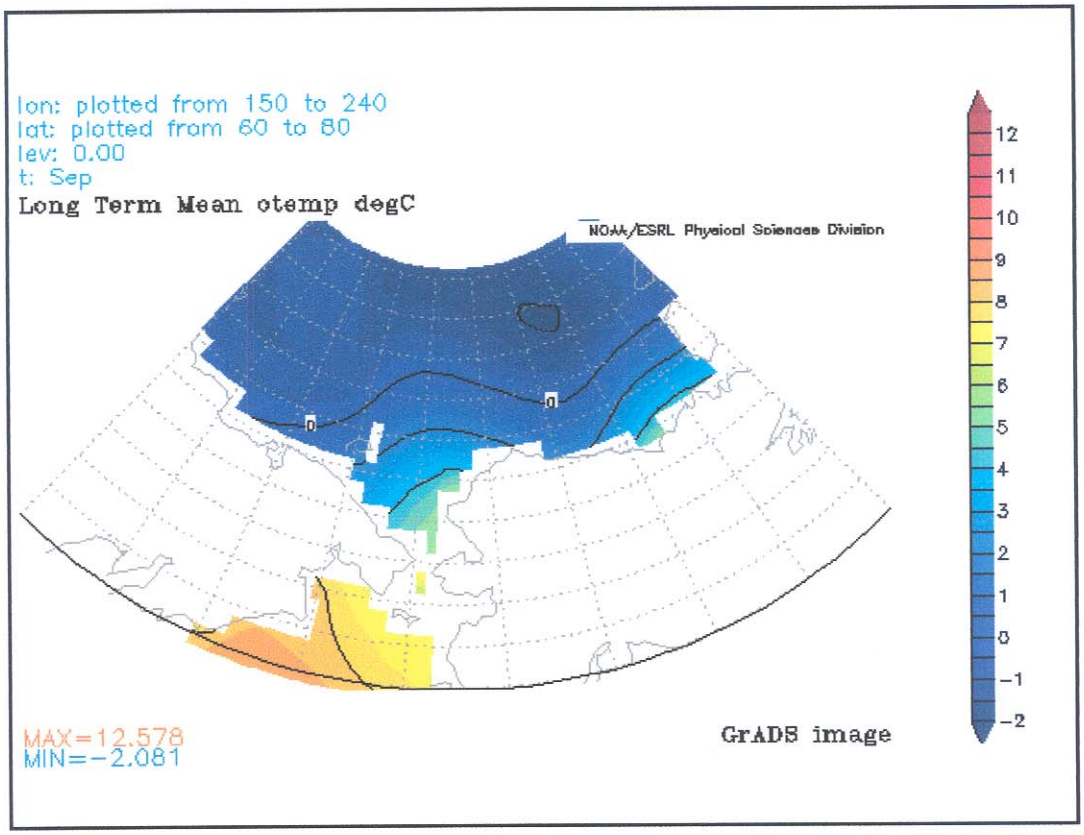

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Apr
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
-2
-2
5
4
3
2
1
0
-1
-2
MAX=5.704
MIN=-2.1
GrADS image

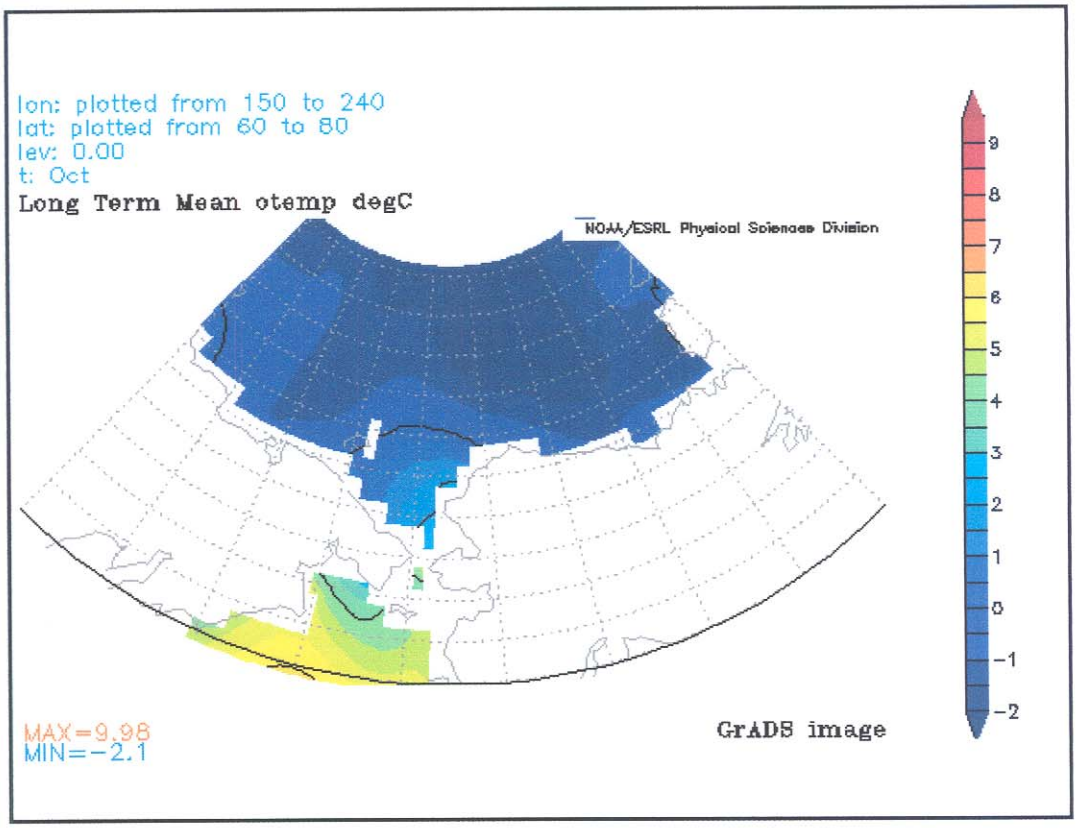

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: May
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
MAX=7.425
MIN=-2.1
GrADS image
7
6
5
4
3
2
1
0
-1
-2

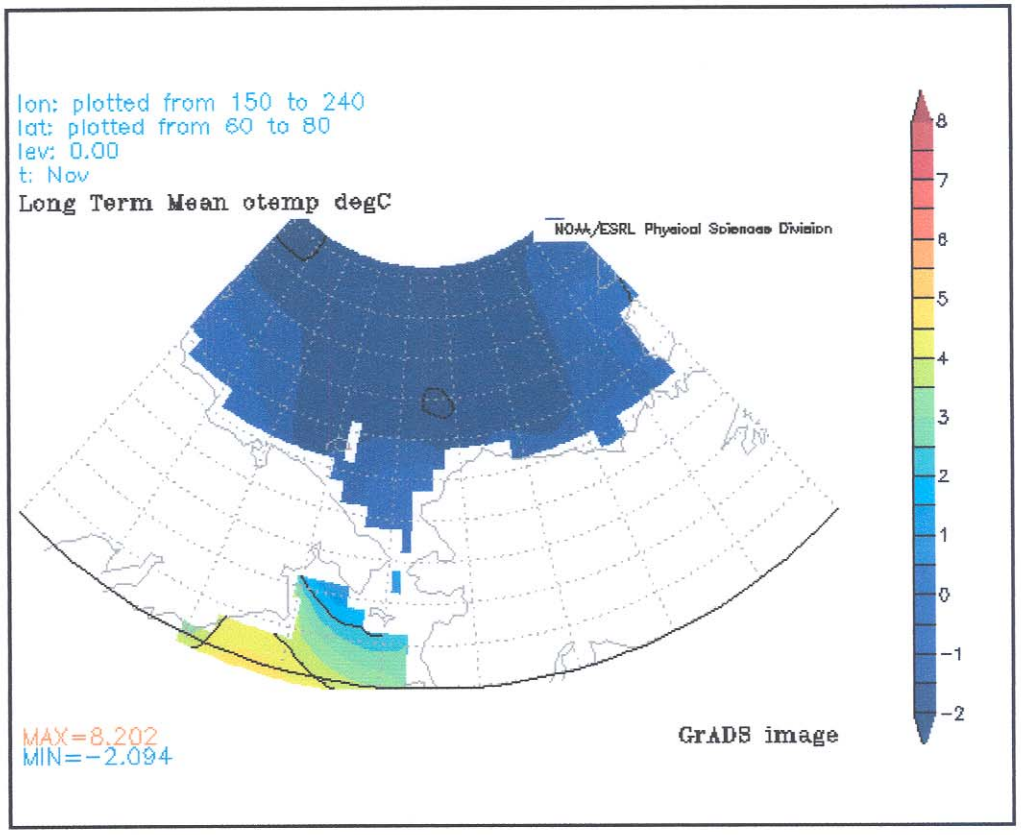

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Jun
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
MAX=9.343
MIN=-2.1
GrADS image
9
8
7
6
5
4
3
2
1
0
-1
-2

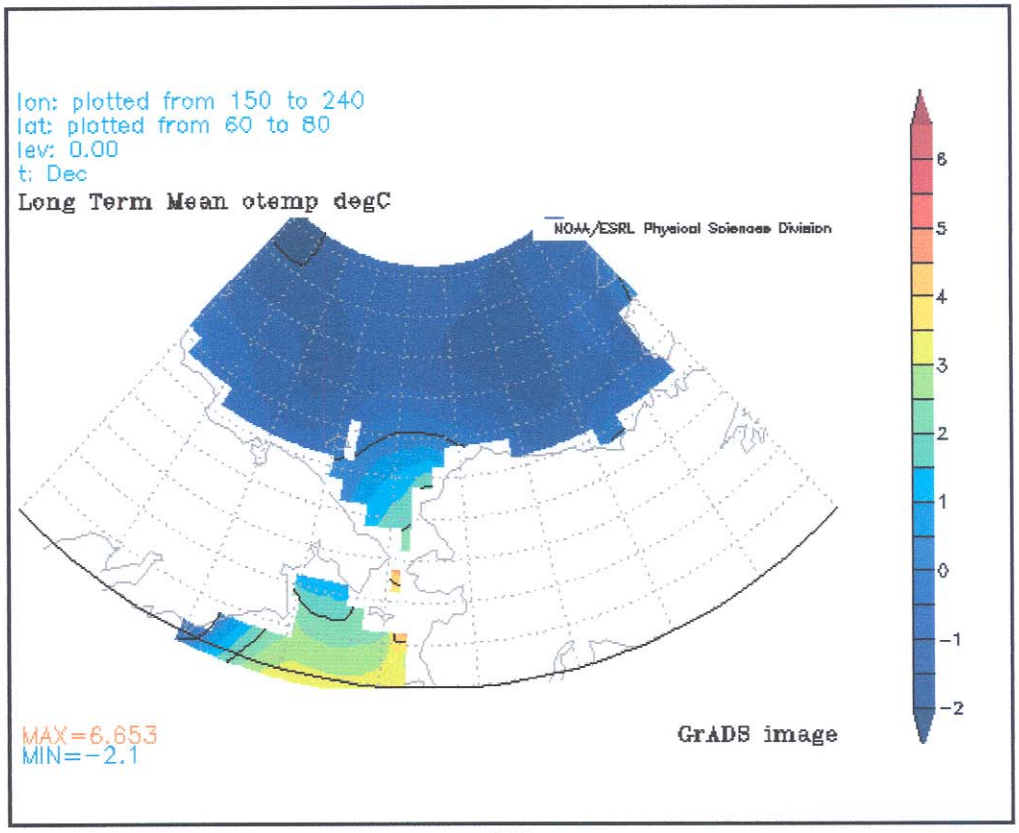

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Jul
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
12.5
11.5
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
MAX=12.541
MIN=-1.861
GrADS image


lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Aug
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
13
11
9
7
5
3
1
-1
MAX=13.993
MIN=-1.851
GrADS image

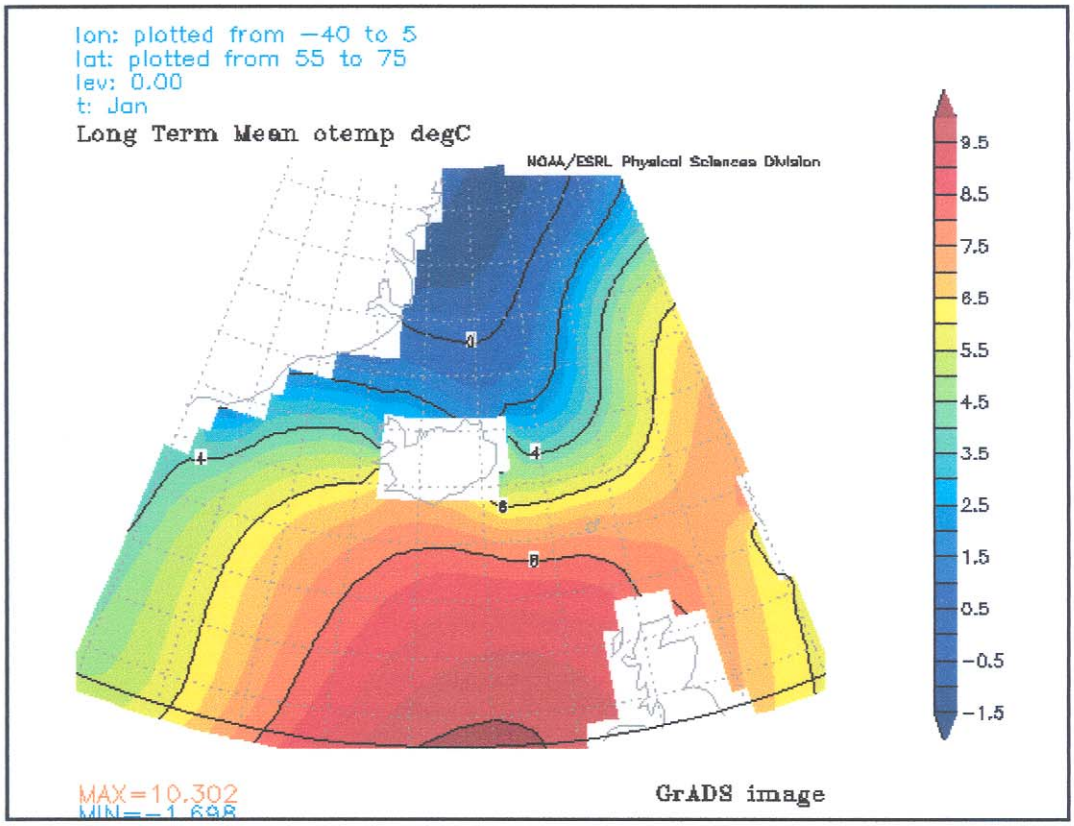

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Sep
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
MAX=12.578
MIN=-2.081
GrADS image
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

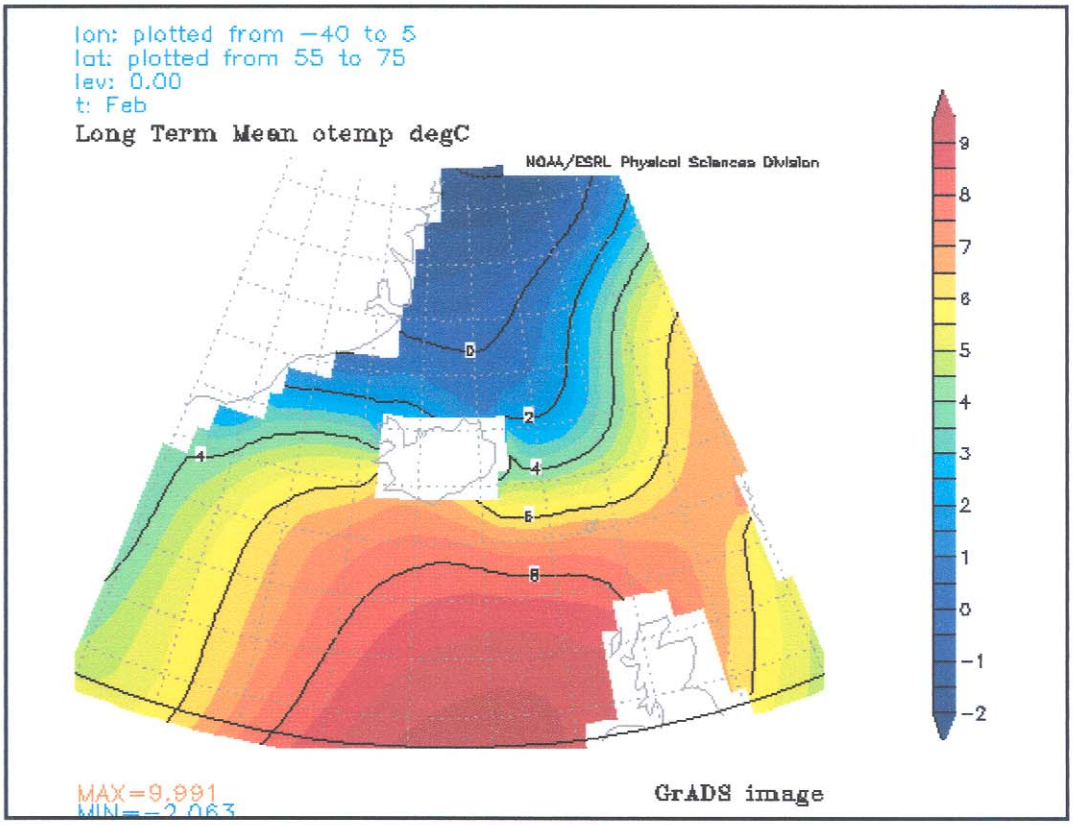

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Oct
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
MAX=9.98
MIN=-2.1
GrADS image
9
8
7
6
5
4
3
2
1
0
-1
-2

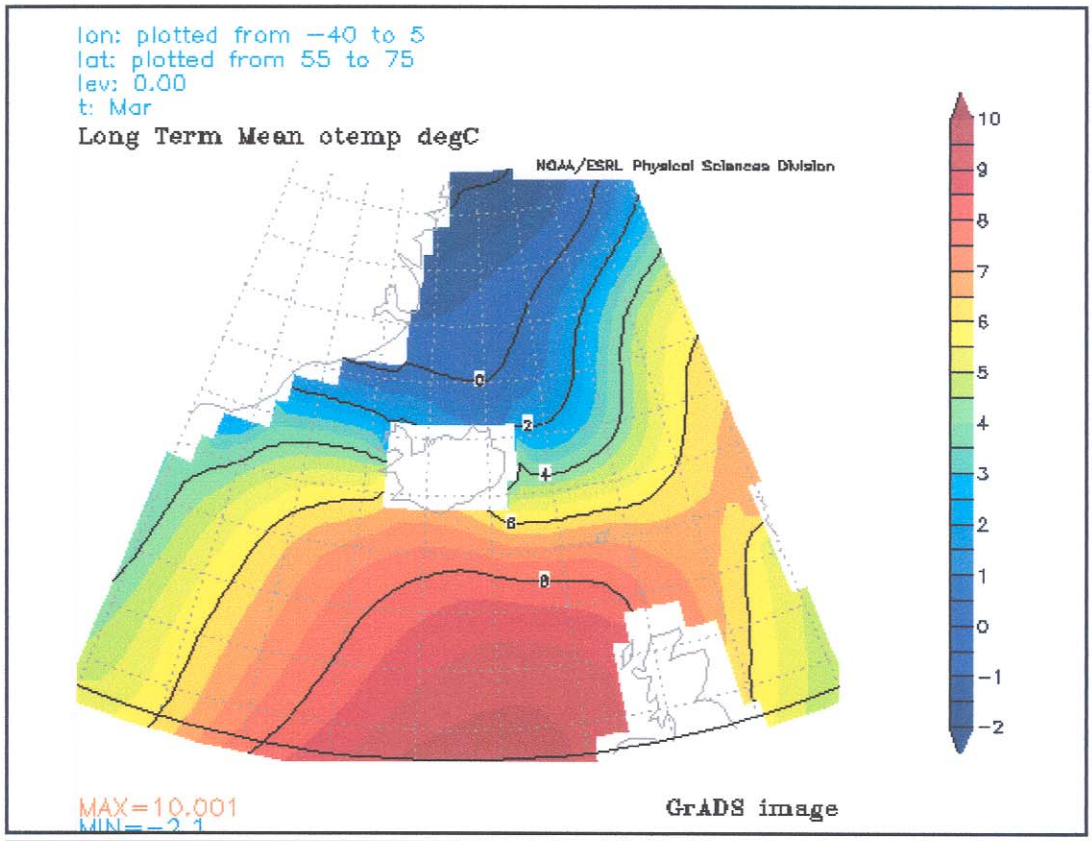

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Nov
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
8
7
6
5
4
3
2
1
0
-1
-2
MAX=8.202
MIN=-2.094
GrADS image

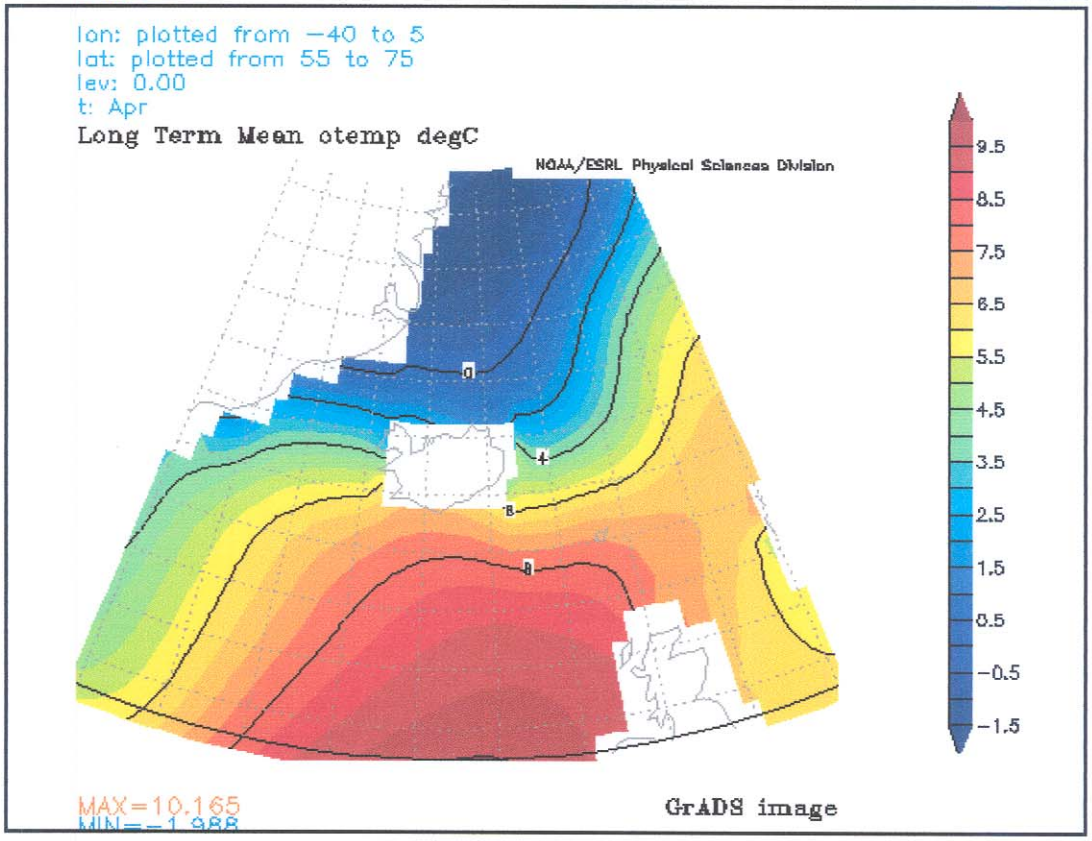

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Dec
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
6
5
4
3
2
1
0
-1
-2
MAX=6.653
MIN=-2.1
GrADS image

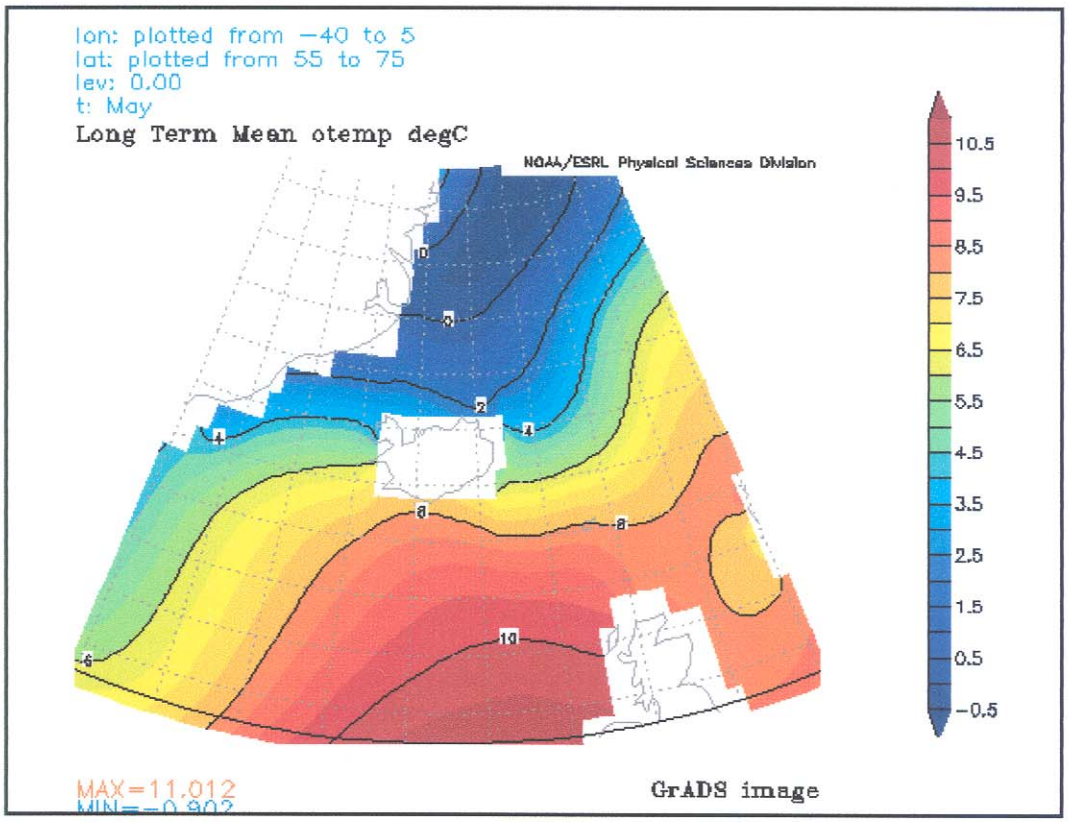
Monthly Isothermal Maps: Iceland
(Levitus) World Ocean Atlas, 1994

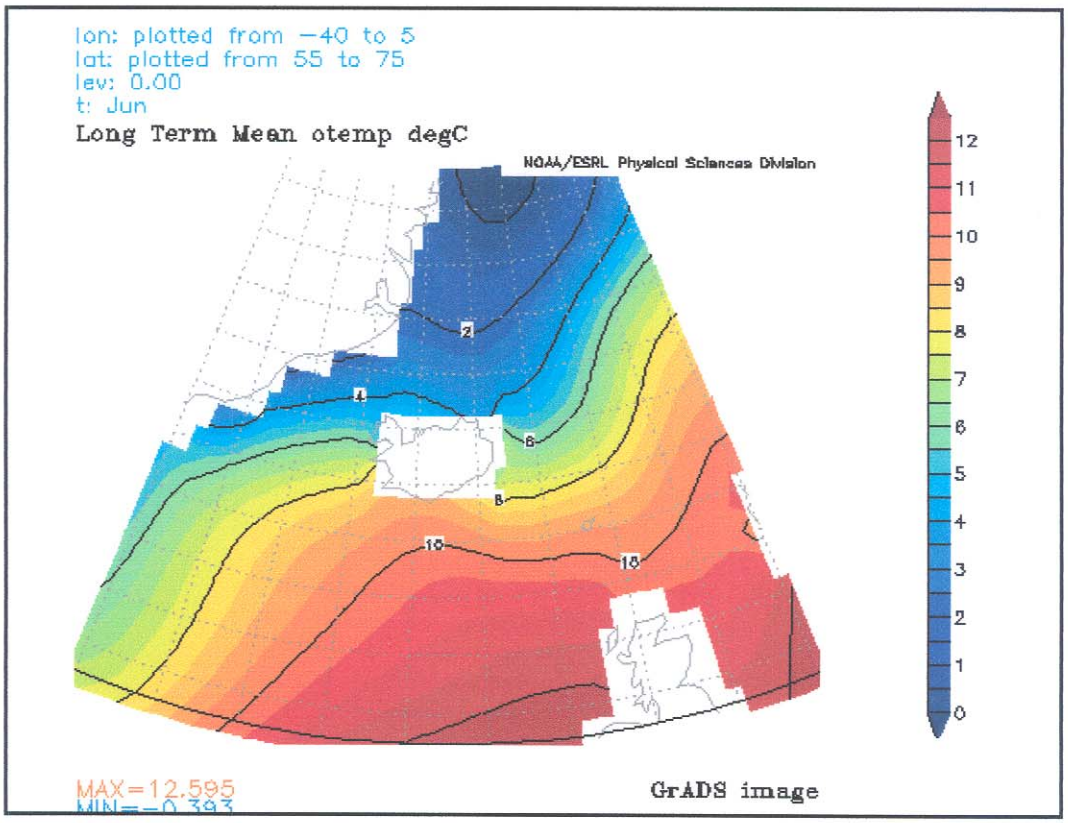

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Jan
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
−0.5
−1.5
MAX=10.302
MIN=−1.698
GrADS image

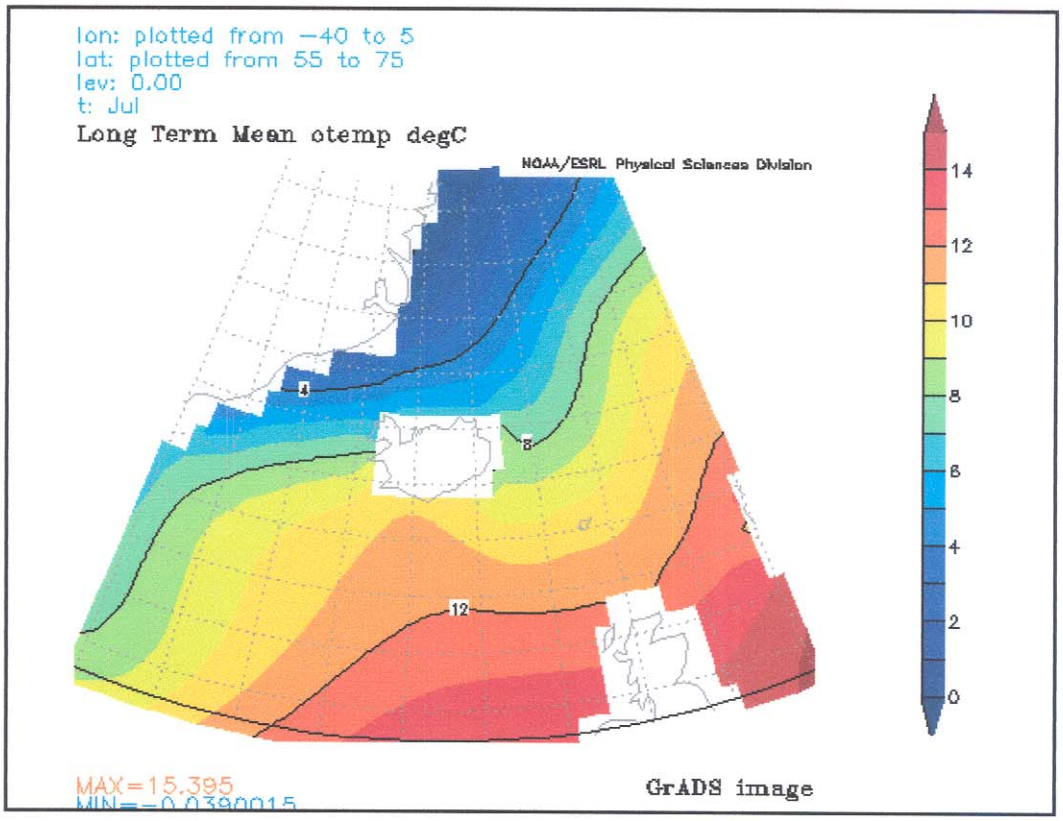

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Feb
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=9.991
MIN=−2.063
GrADS image

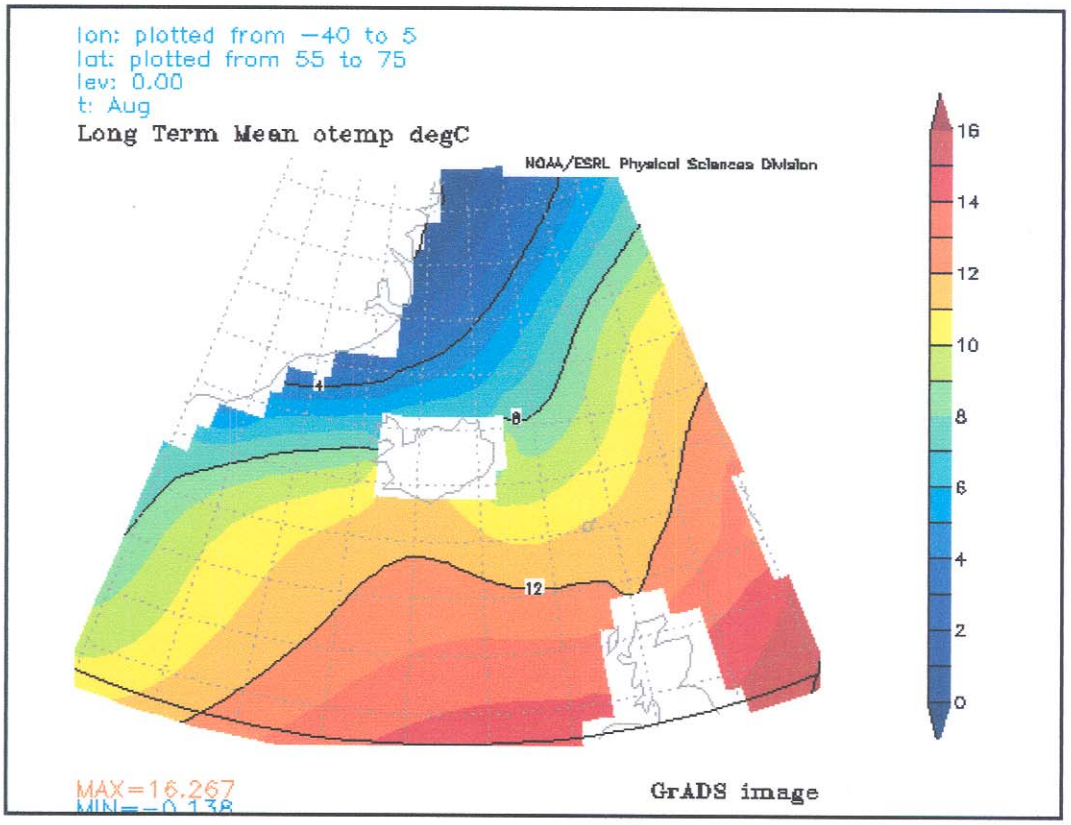

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Mar
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
10
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=10.001
GrADS image

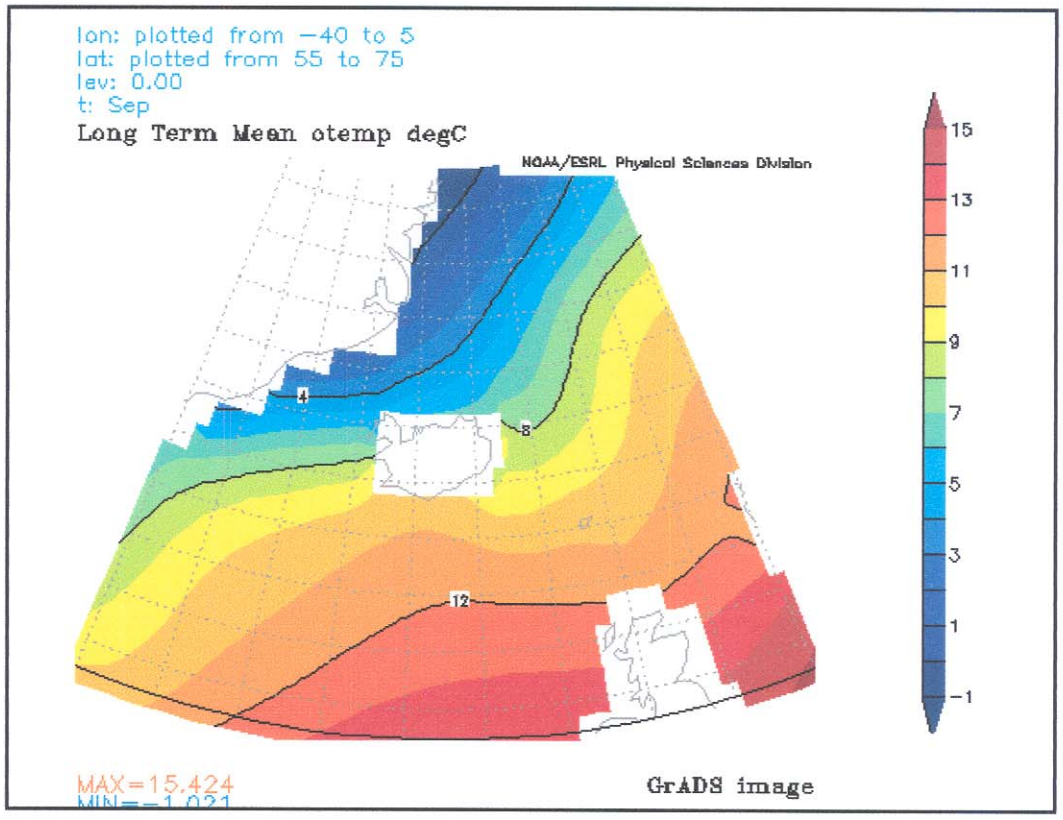

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Apr
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
−0.5
−1.5
MAX=10.165
GrADS image

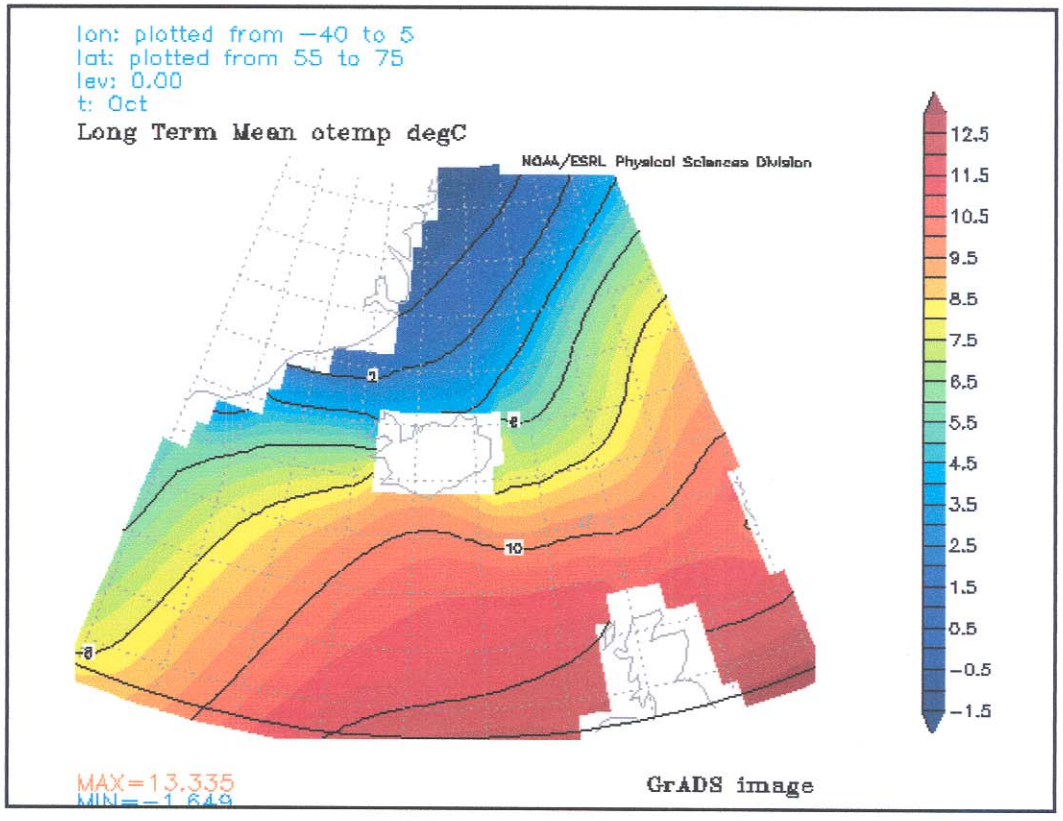

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: May
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
−0.5
MAX=11.012
GrADS image

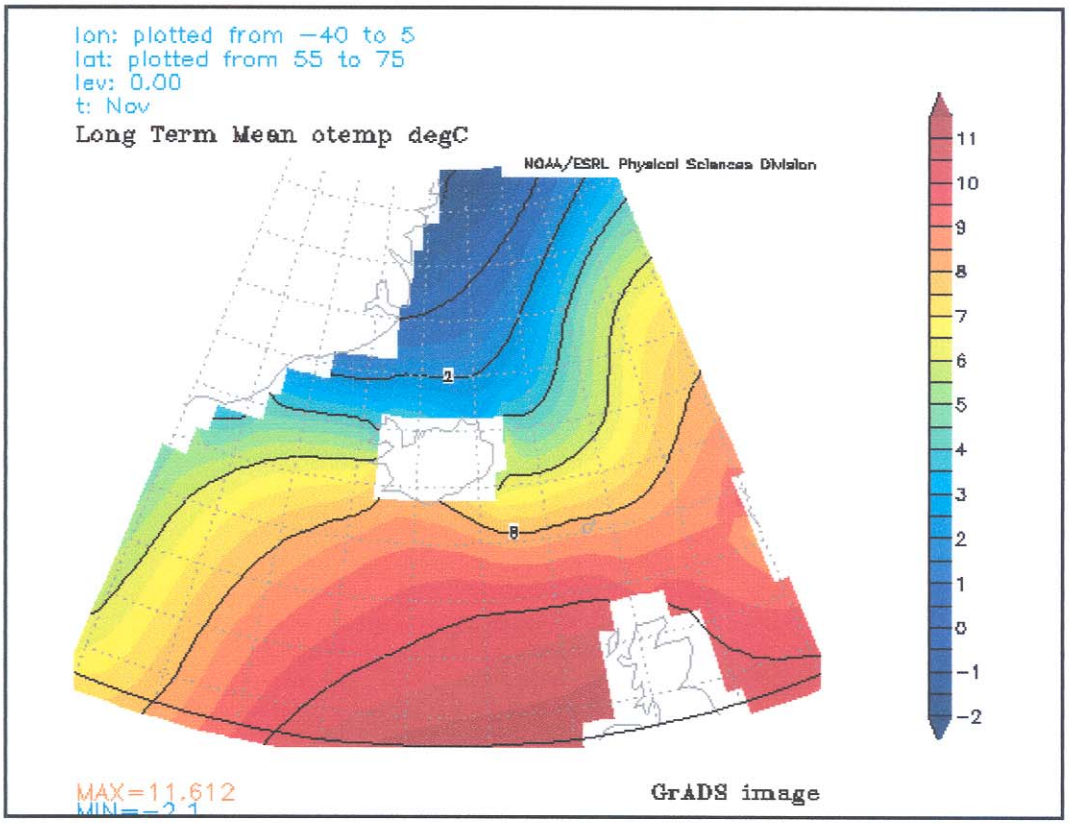

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Jun
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
12
11
10
9
8
7
6
5
4
3
2
1
0
MAX=12.595
GrADS image

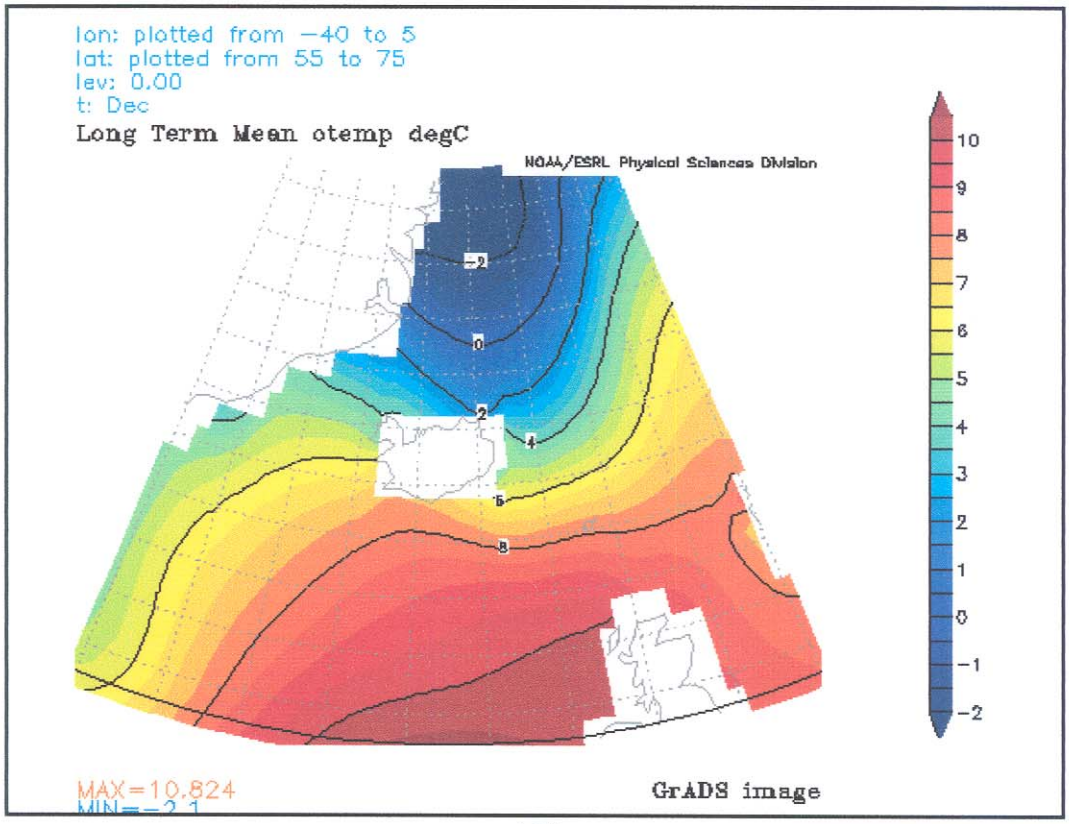

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Jul
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
4
8
12
14
12
10
8
6
4
2
0
MAX=15.395
GrADS image


lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Aug
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
4
8
12
16
14
12
10
8
6
4
2
0
MAX=16.267
GrADS image

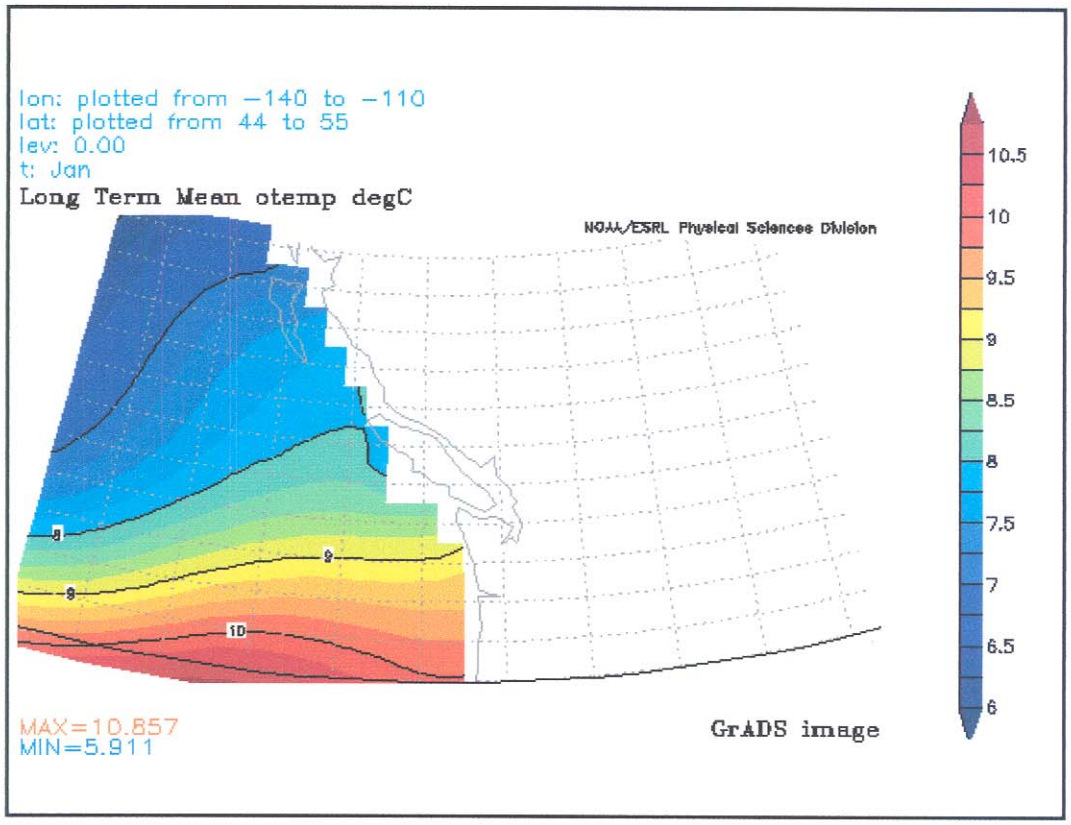

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Sep
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
15
13
11
9
7
5
3
1
−1
4
8
12
MAX=15.424
GrADS image

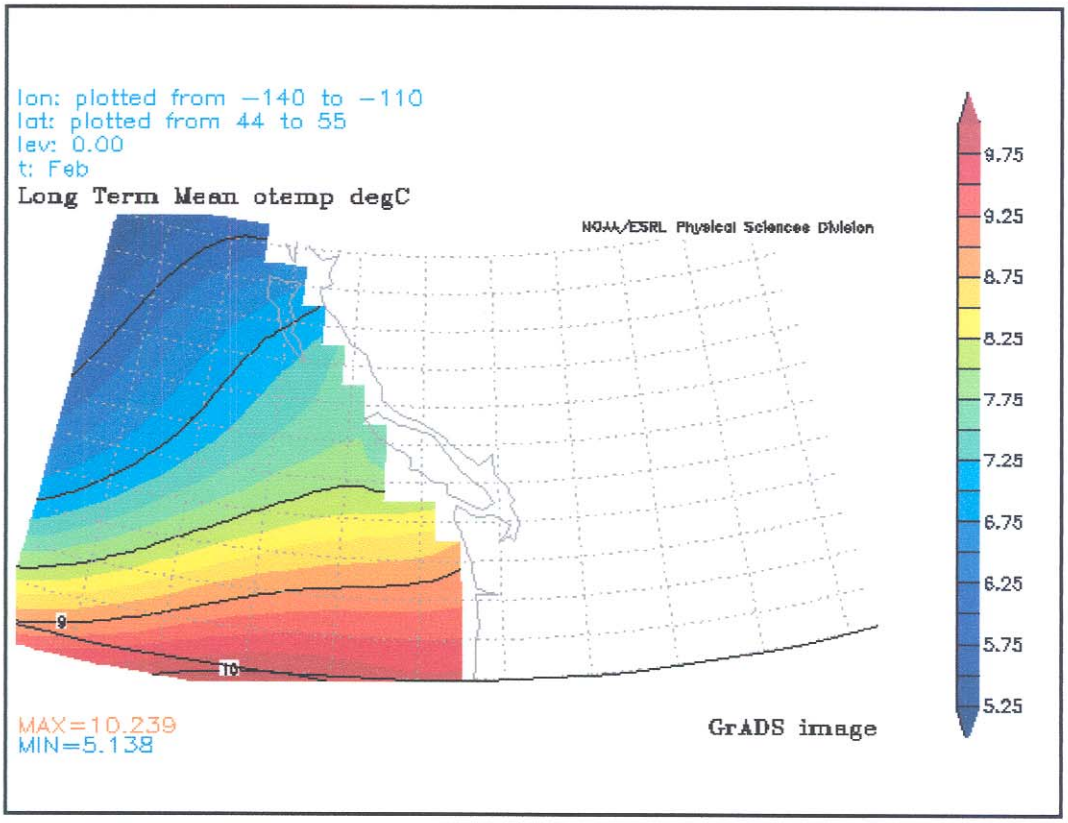

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Oct
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
12.5
11.5
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
−0.5
−1.5
2
6
10
8
MAX=13.335
GrADS image

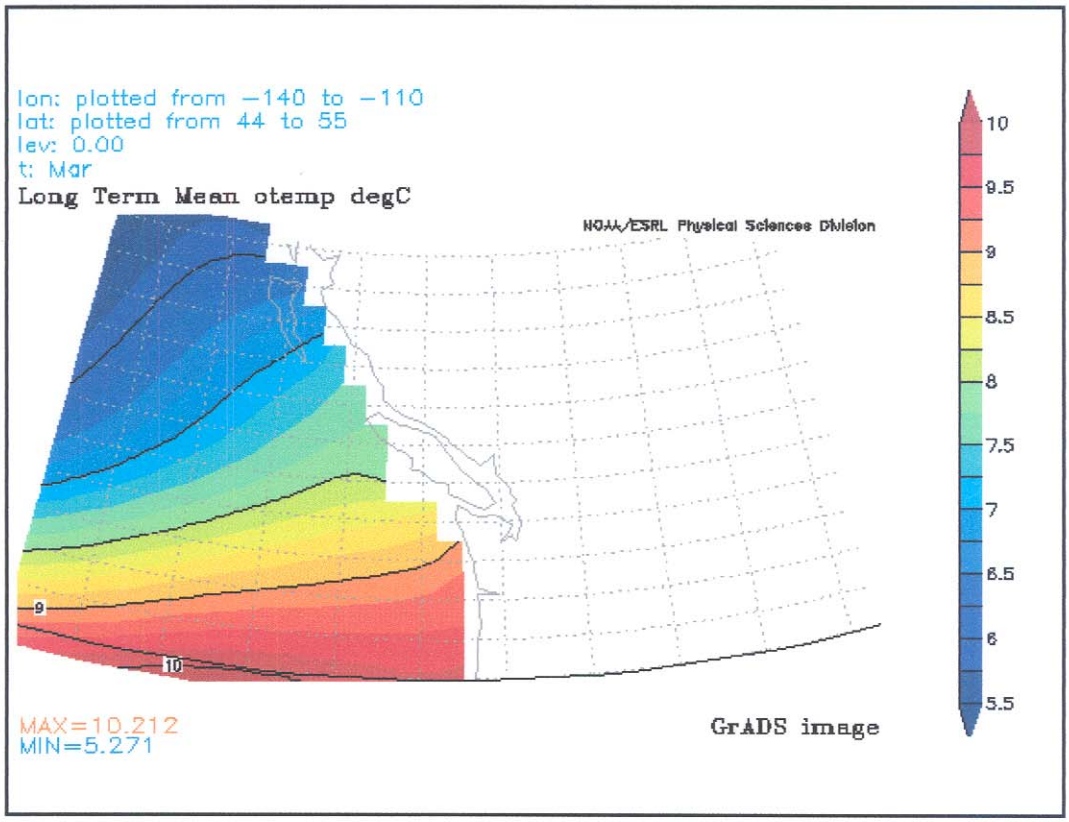

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Nov
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
11
10
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=11.612
GrADS image

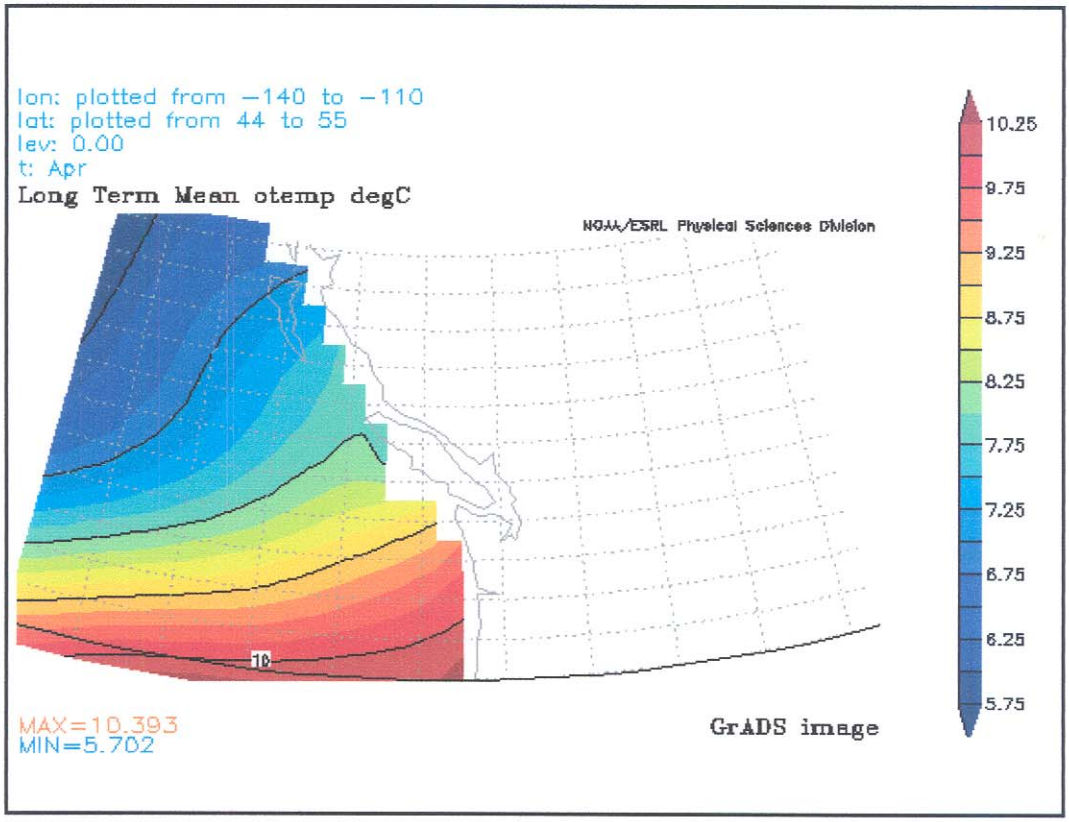

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Dec
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
10
9
8
7
6
5
4
3
2
1
0
−1
−2
MAX=10.824
GrADS image

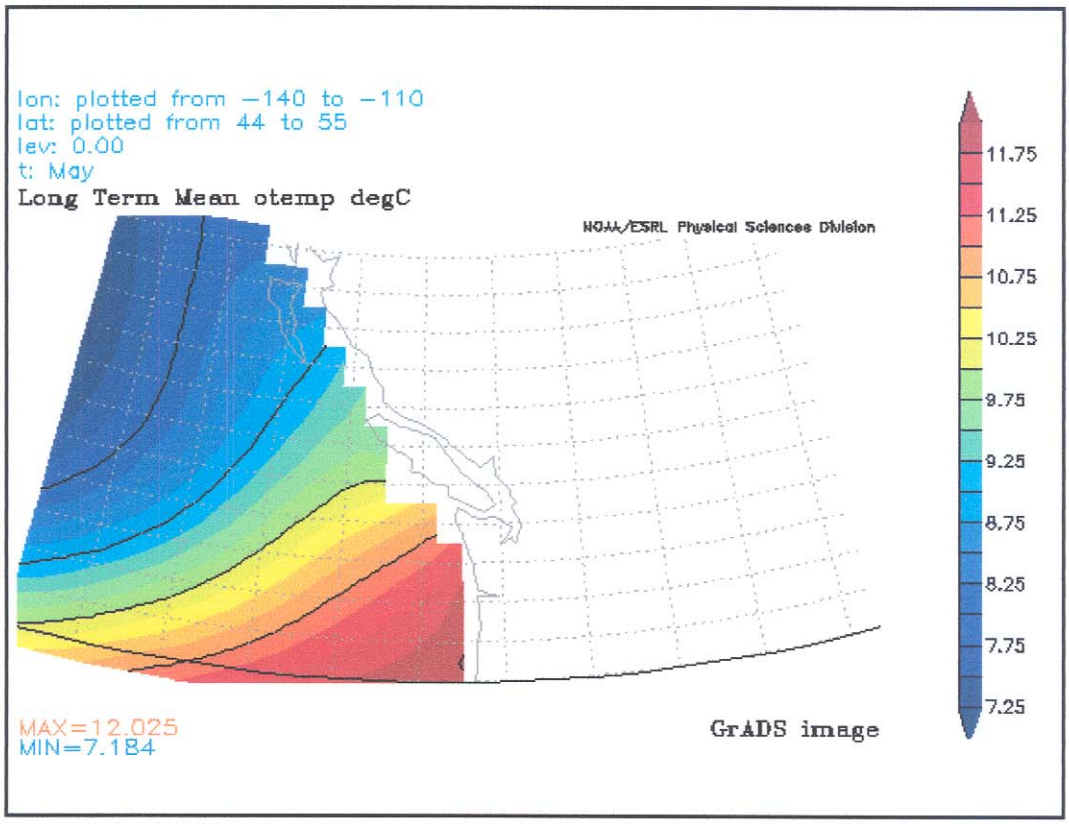
Monthly Isothermal Maps: Washington
(Levitus) World Ocean Atlas, 1994

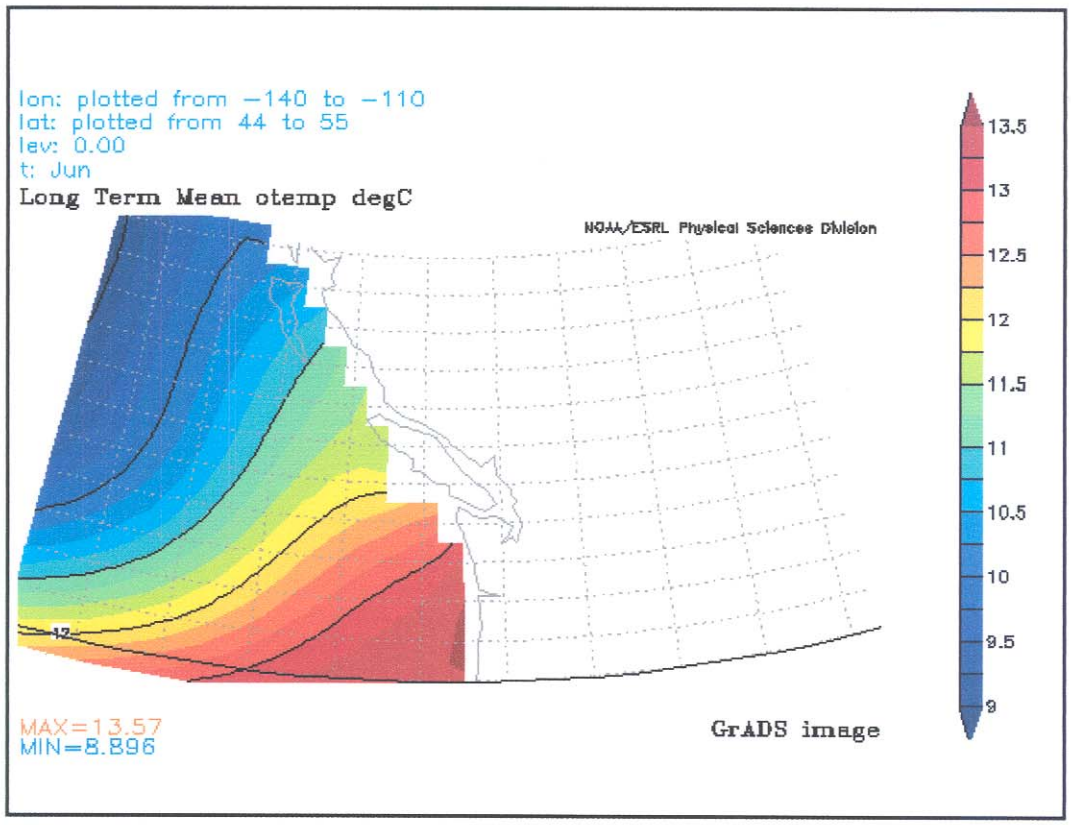

lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Jan
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
MAX=10.857
MIN=5.911
GrADS image

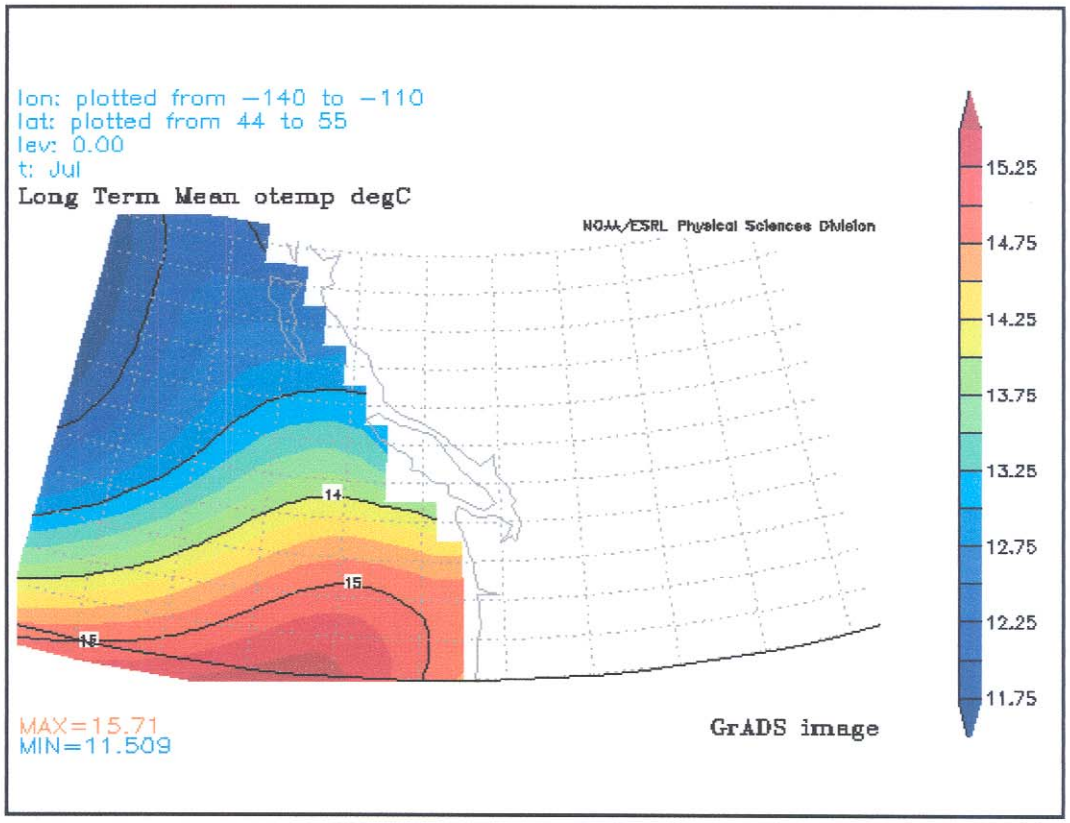

lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Feb
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
9.75
9.25
8.75
8.25
7.75
7.25
6.75
6.25
5.75
5.25
MAX=10.239
MIN=5.138
GrADS image

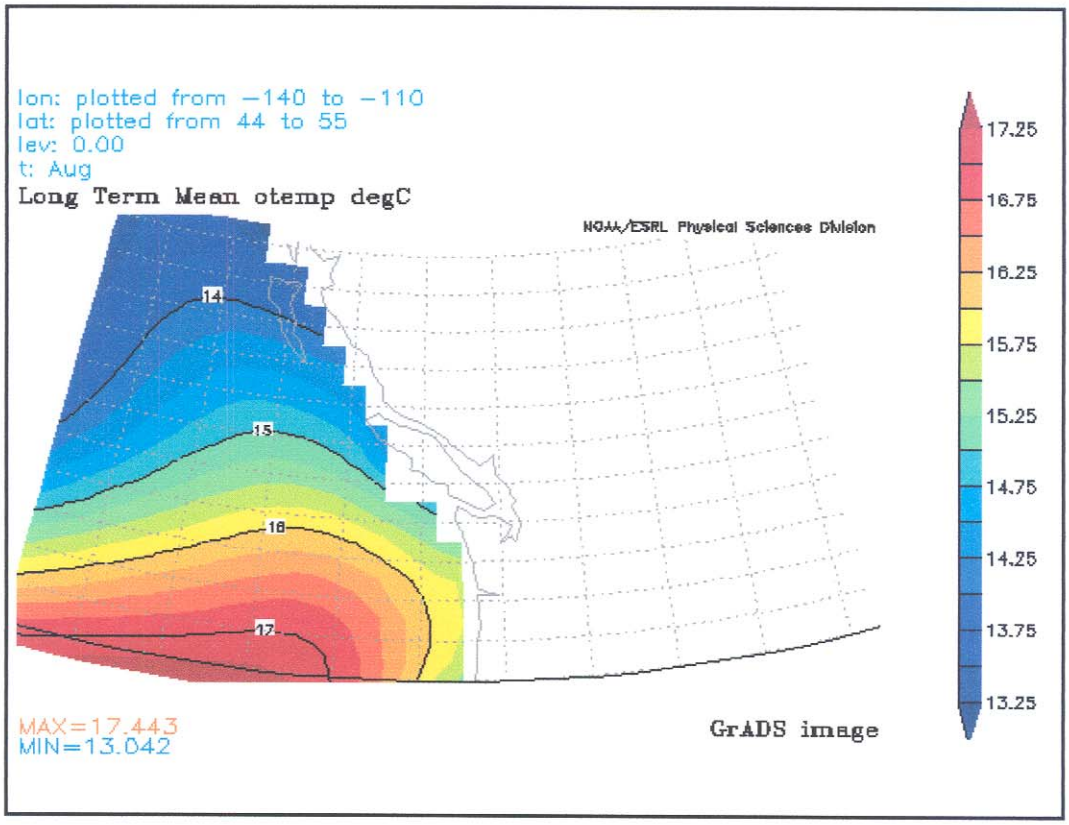

lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Mar
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
9
10
MAX=10.212
MIN=5.271
GrADS image
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5

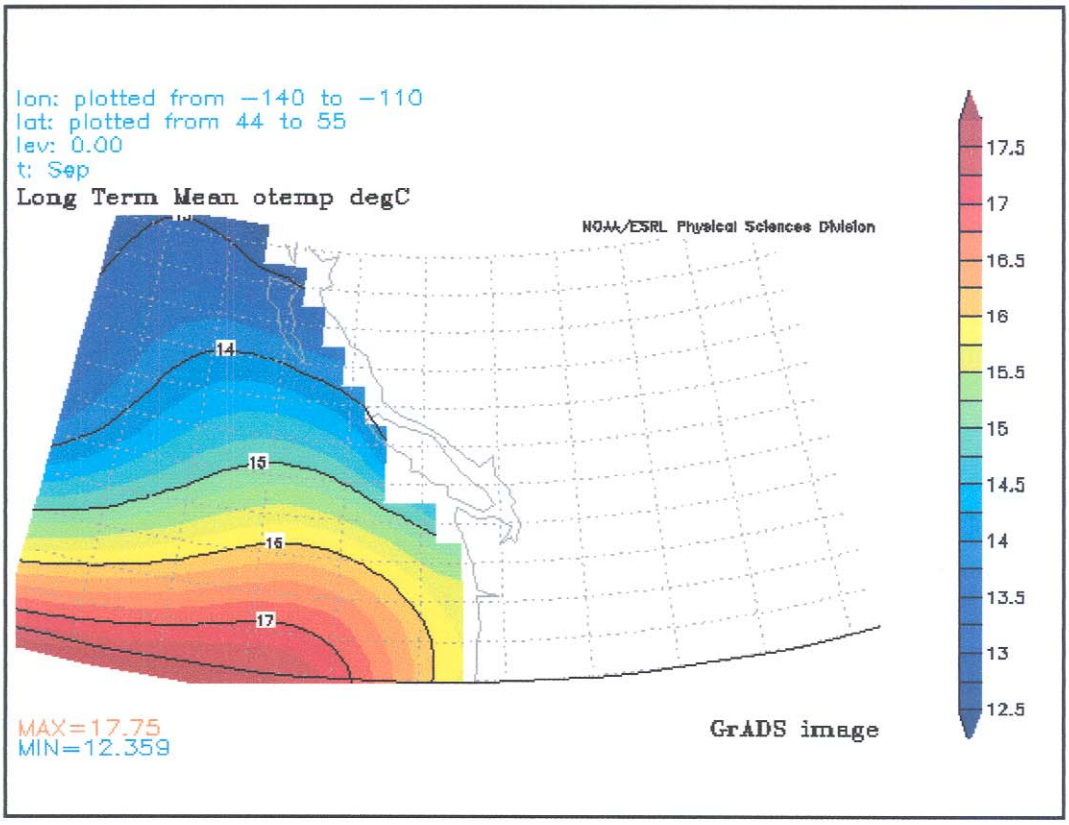

lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Apr
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
10
MAX=10.393
MIN=5.702
GrADS image
10.25
9.75
9.25
8.75
8.25
7.75
7.25
6.75
6.25
5.75

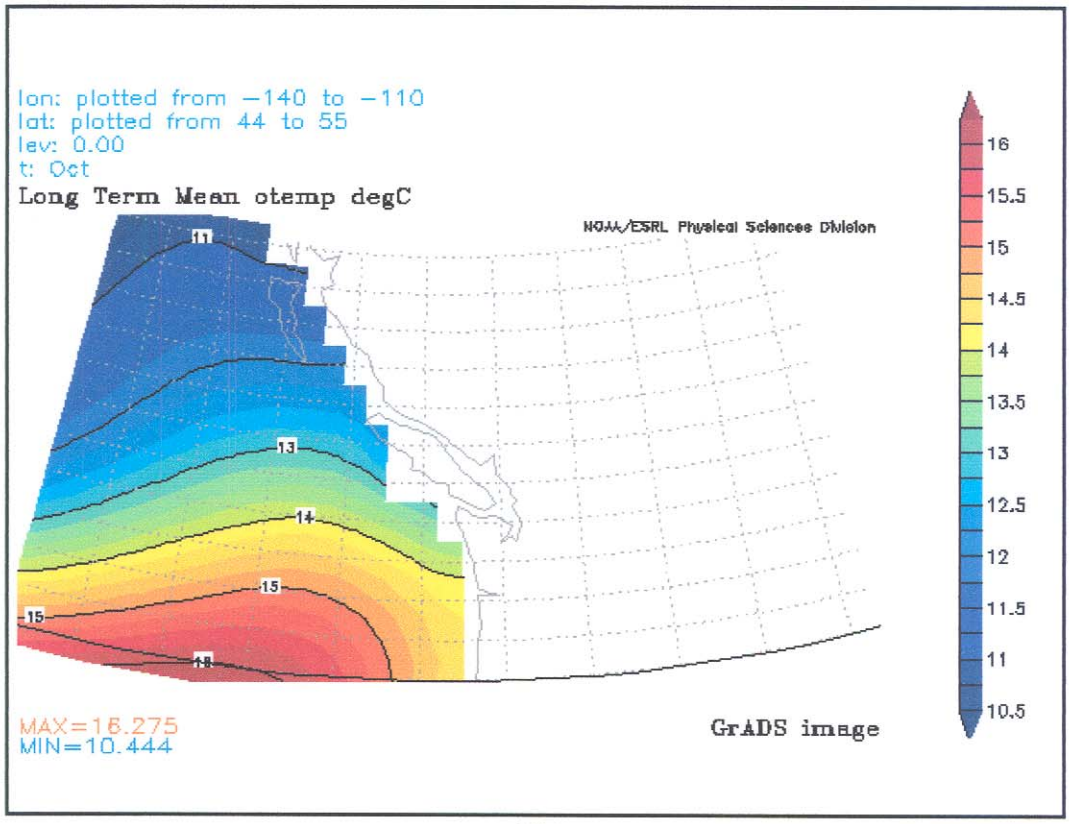

lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: May
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
11.75
11.25
10.75
10.25
9.75
9.25
8.75
8.25
7.75
7.25
MAX=12.025
MIN=7.184
GrADS image

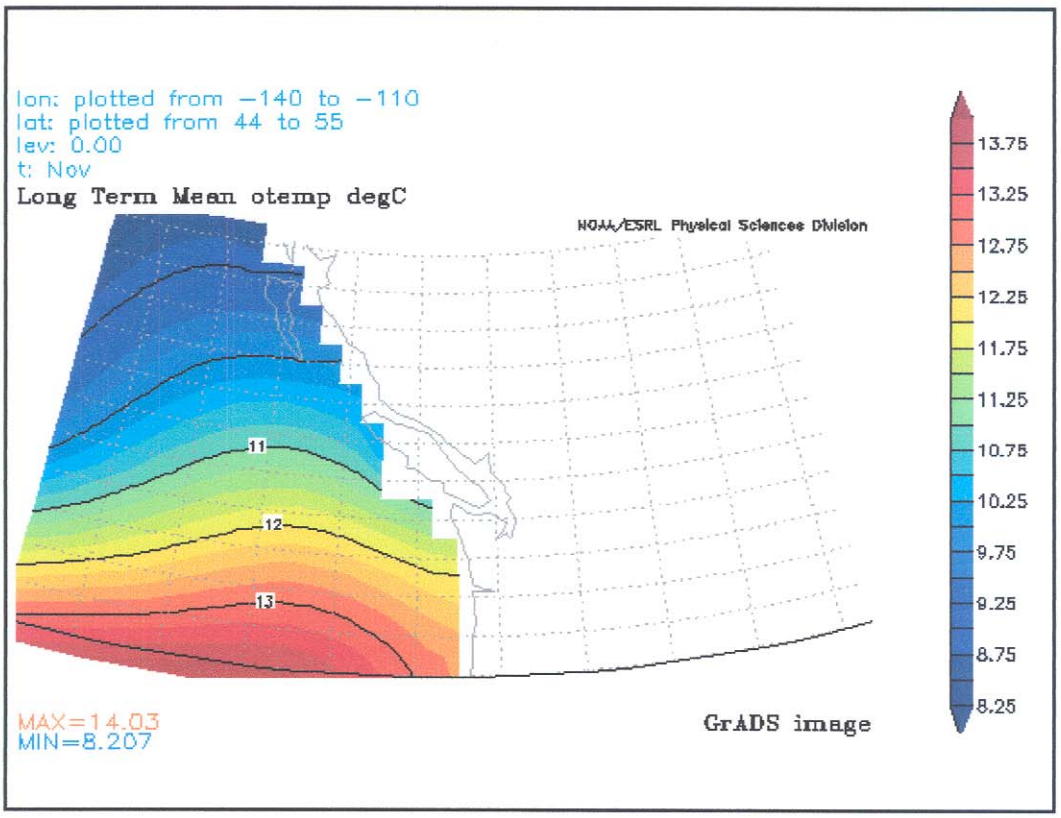

lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Jun
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
MAX=13.57
MIN=8.896
GrADS image

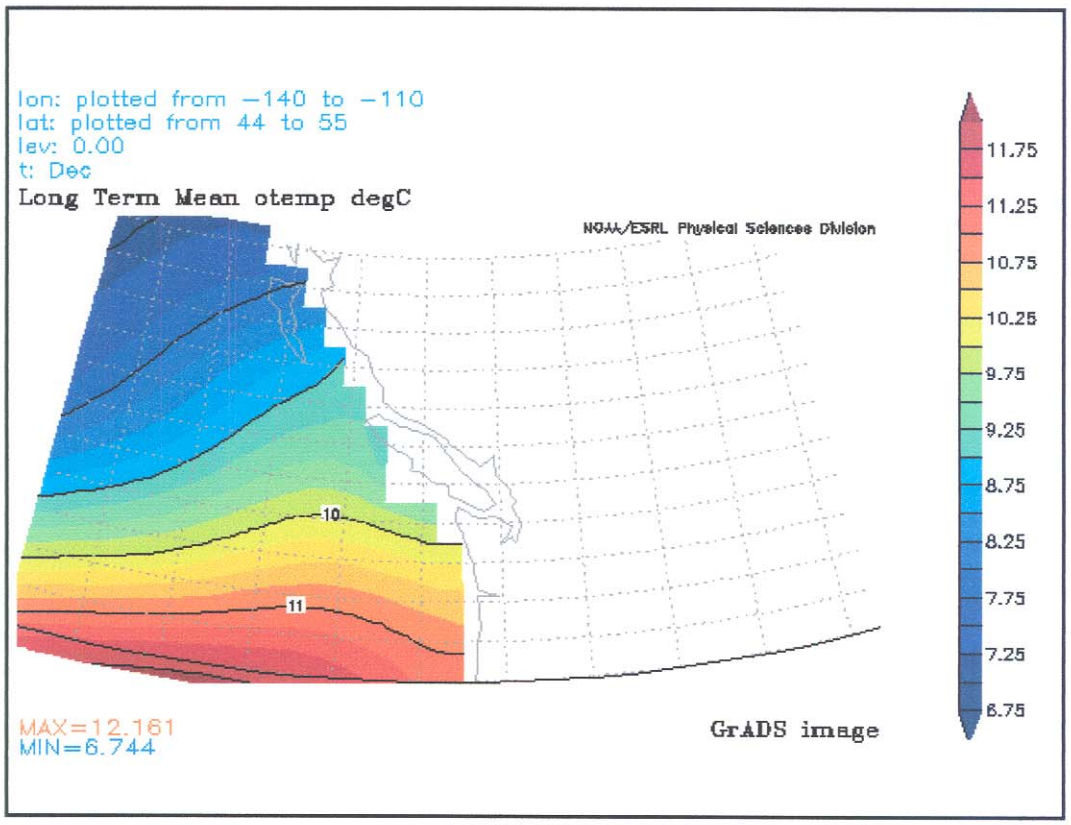

lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Jul
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
14
15
15
15.25
14.75
14.25
13.75
13.25
12.75
12.25
11.75
MAX=15.71
MIN=11.509
GrADS image


lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Aug
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
14
15
16
17
17.25
16.75
16.25
15.75
15.25
14.75
14.25
13.75
13.25
MAX=17.443
MIN=13.042
GrADS image


lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Sep
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
14
15
16
17
MAX=17.75
MIN=12.359
GrADS image
17.5
17
16.5
16
15.5
15
14.5
14
13.5
13
12.5


lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Oct
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
11
13
14
15
15
16
MAX=16.275
MIN=10.444
GrADS image
16
15.5
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5

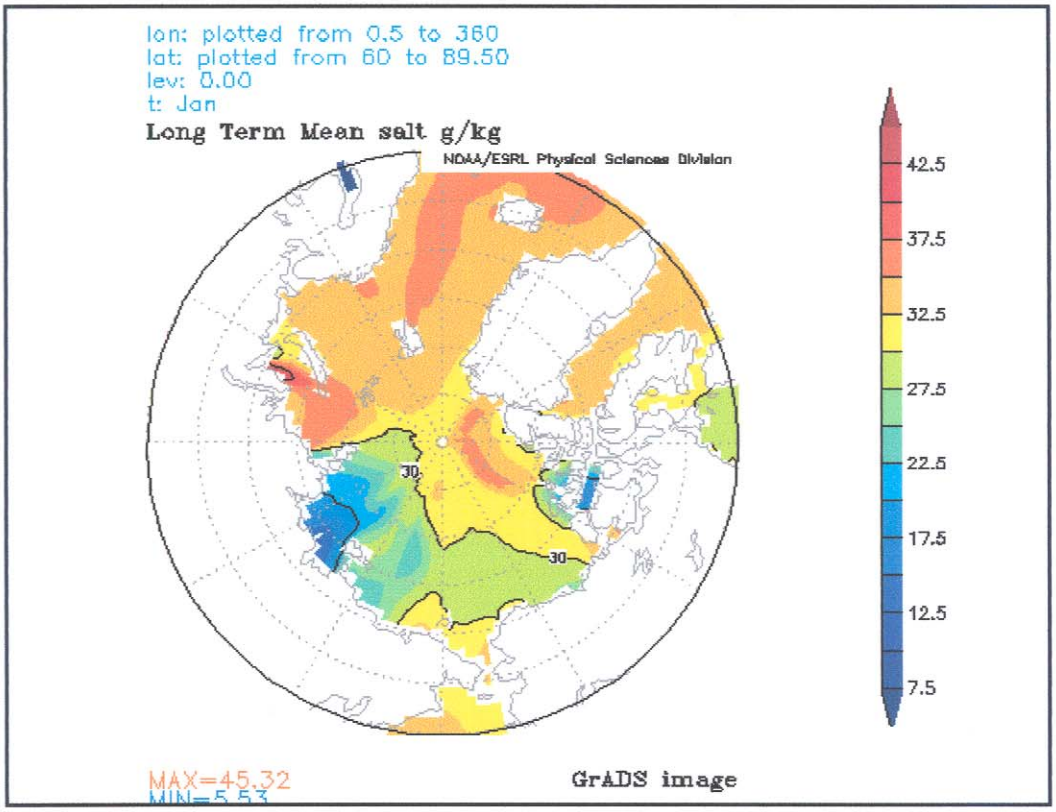

lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Nov
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
11
12
13
MAX=14.03
MIN=8.207
GrADS image
13.75
13.25
12.75
12.25
11.75
11.25
10.75
10.25
9.75
9.25
8.75
8.25

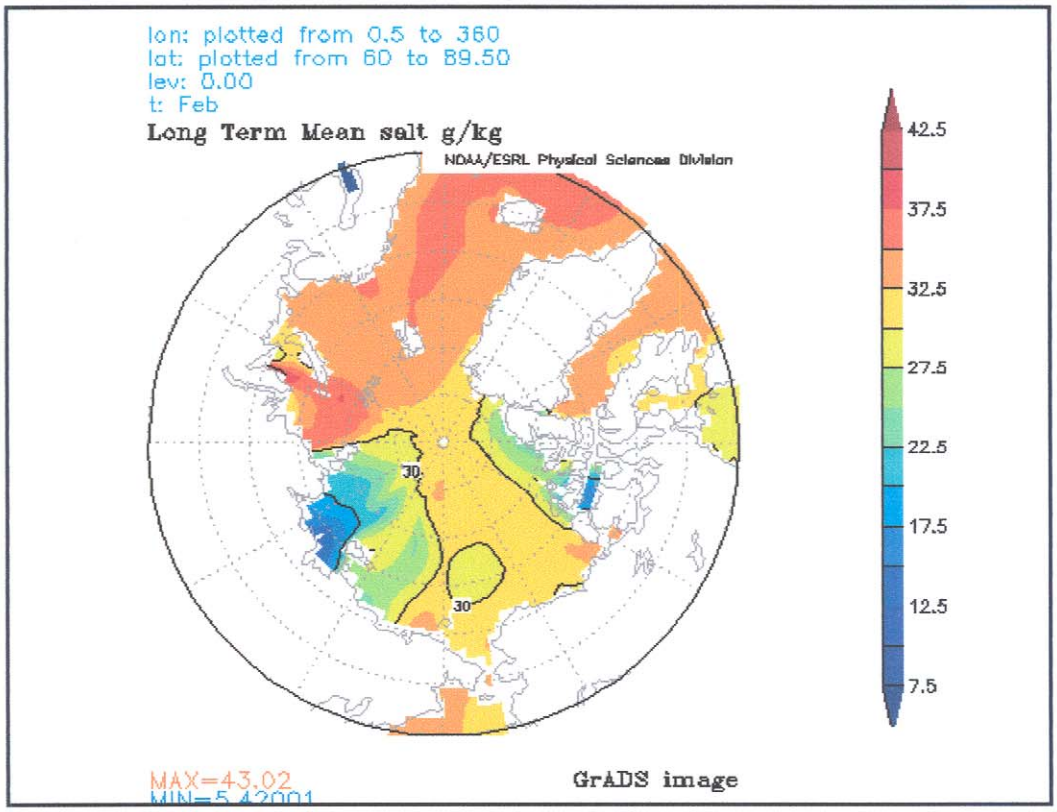

lon: plotted from −140 to −110
lat: plotted from 44 to 55
lev: 0.00
t: Dec
Long Term Mean otemp degC
NOAA/ESRL Physical Sciences Division
10
11
MAX=12.161
MIN=6.744
GrADS image
11.75
11.25
10.75
10.25
9.75
9.25
8.75
8.25
7.75
7.25
6.75

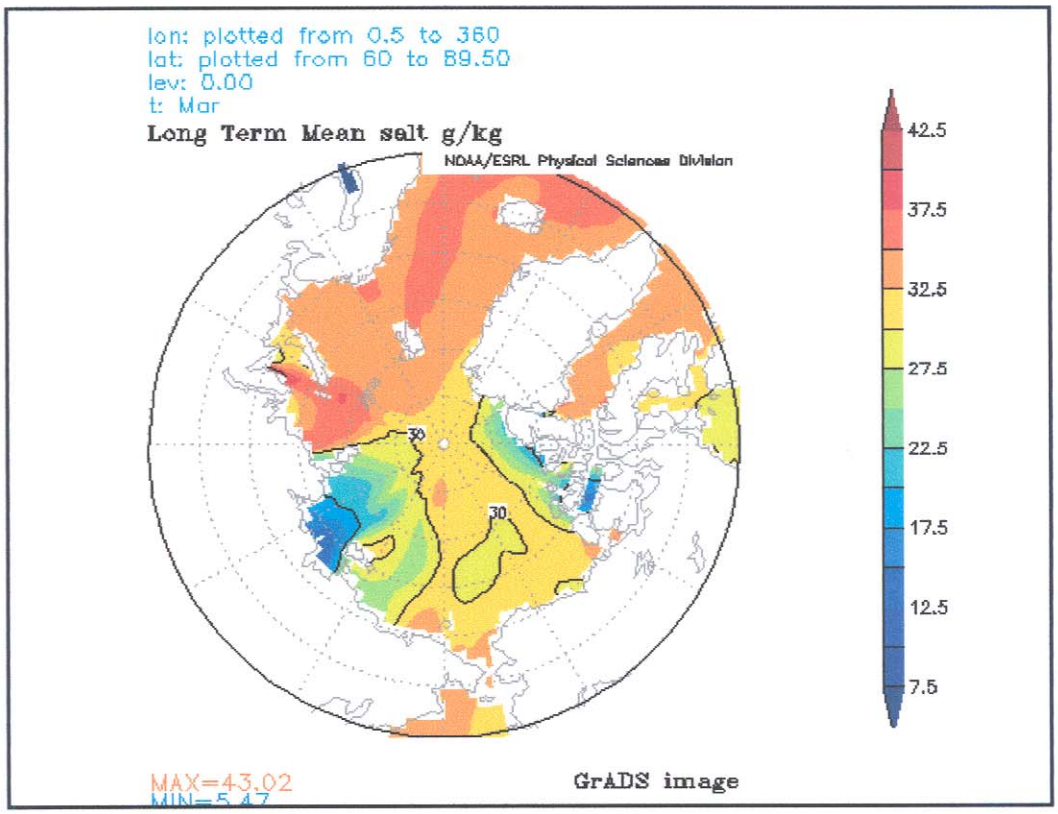
APPENDIX 3

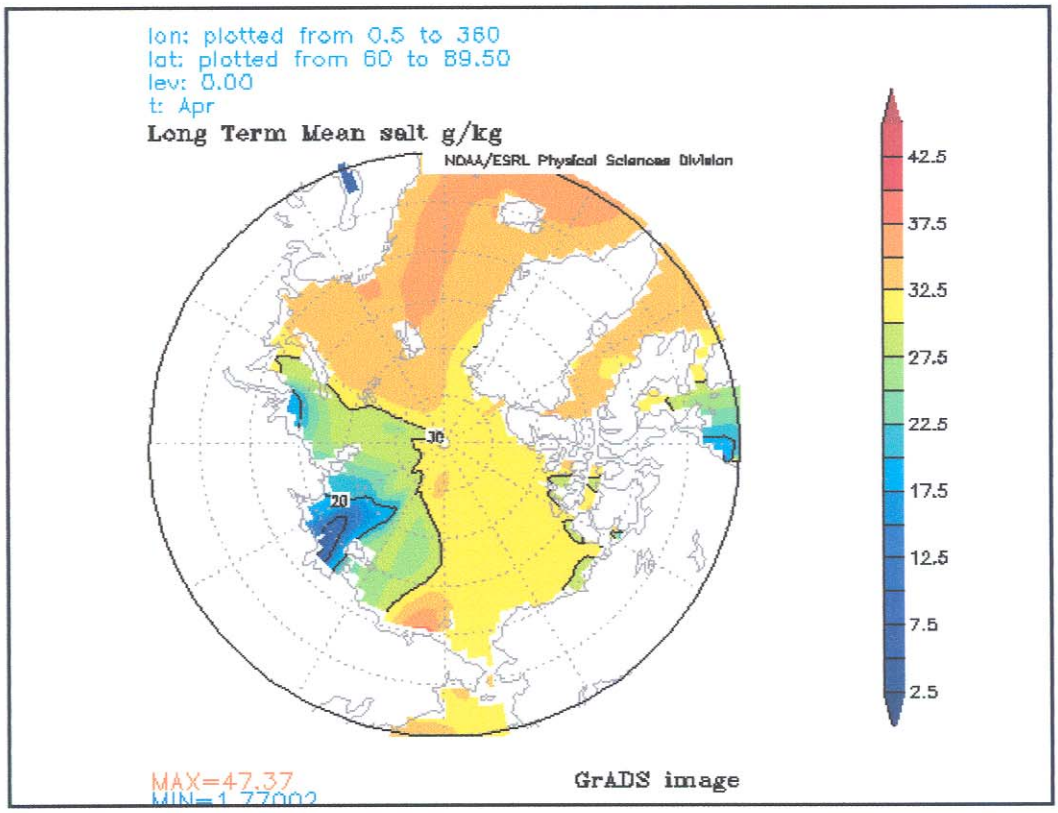
Monthly Isosalinity Maps:
Arctic Ocean, Chukchi Sea, Iceland and Washington
(Levitus) World Ocean Atlas, 1994

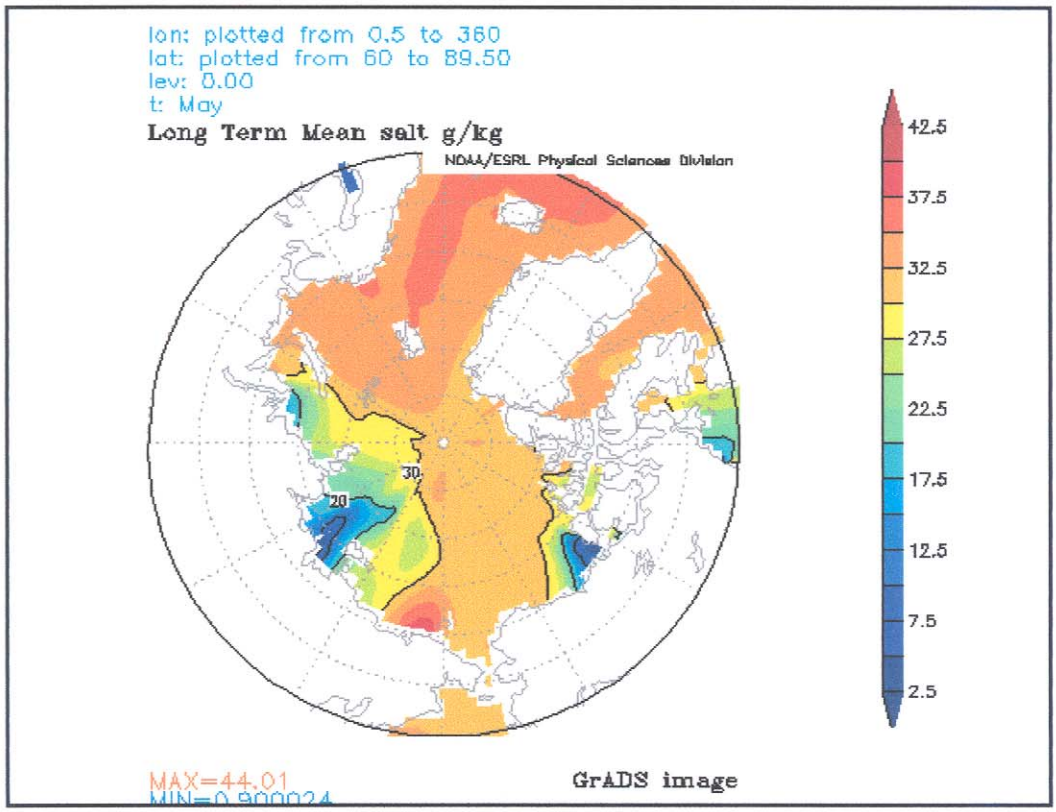
Monthly Isosalinity Maps: Arctic Ocean
(Levitus) World Ocean Atlas, 1994

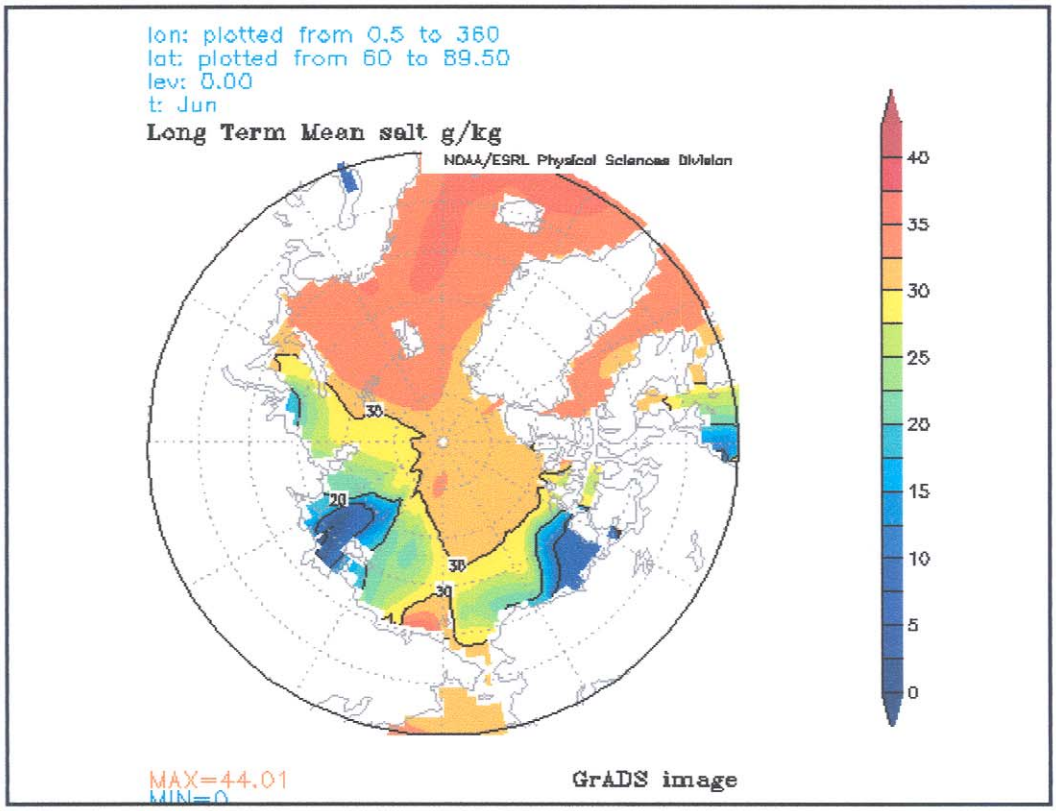

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Jan
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
30
30
42.5
37.5
32.5
27.5
22.5
17.5
12.5
7.5
MAX=45.32
MIN=5.53
GrADS image

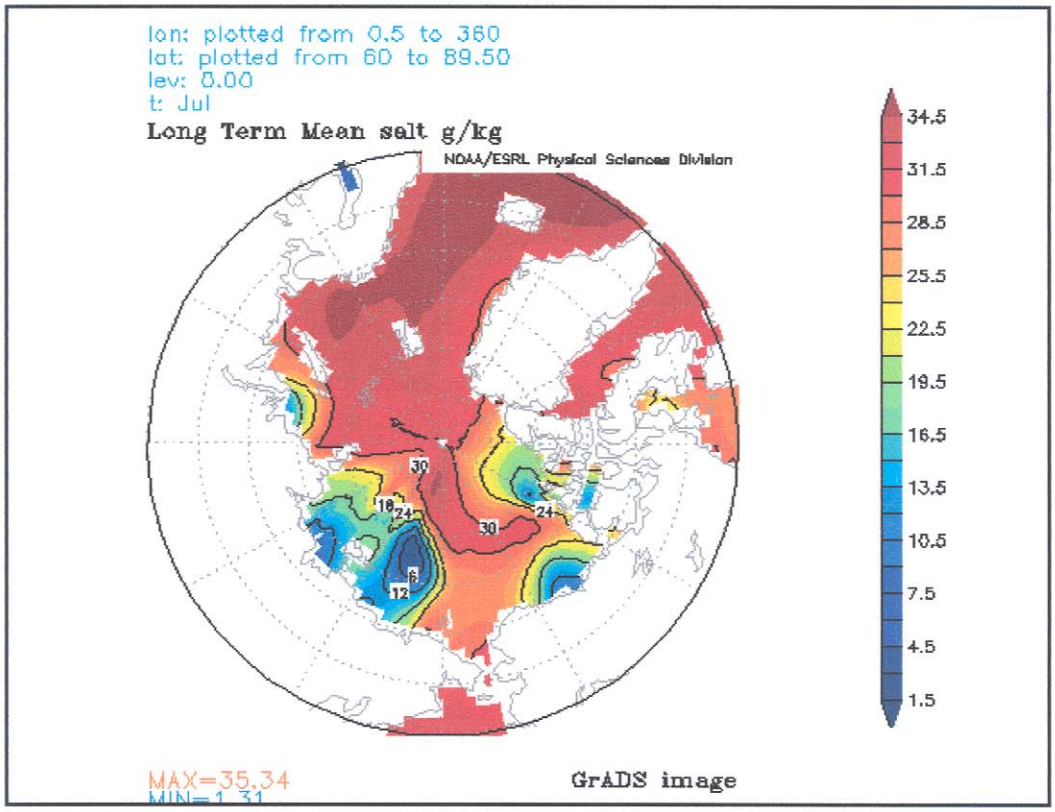

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Feb
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
30
30
42.5
37.5
32.5
27.5
22.5
17.5
12.5
7.5
MAX=43.02
MIN=5.42001
GrADS image

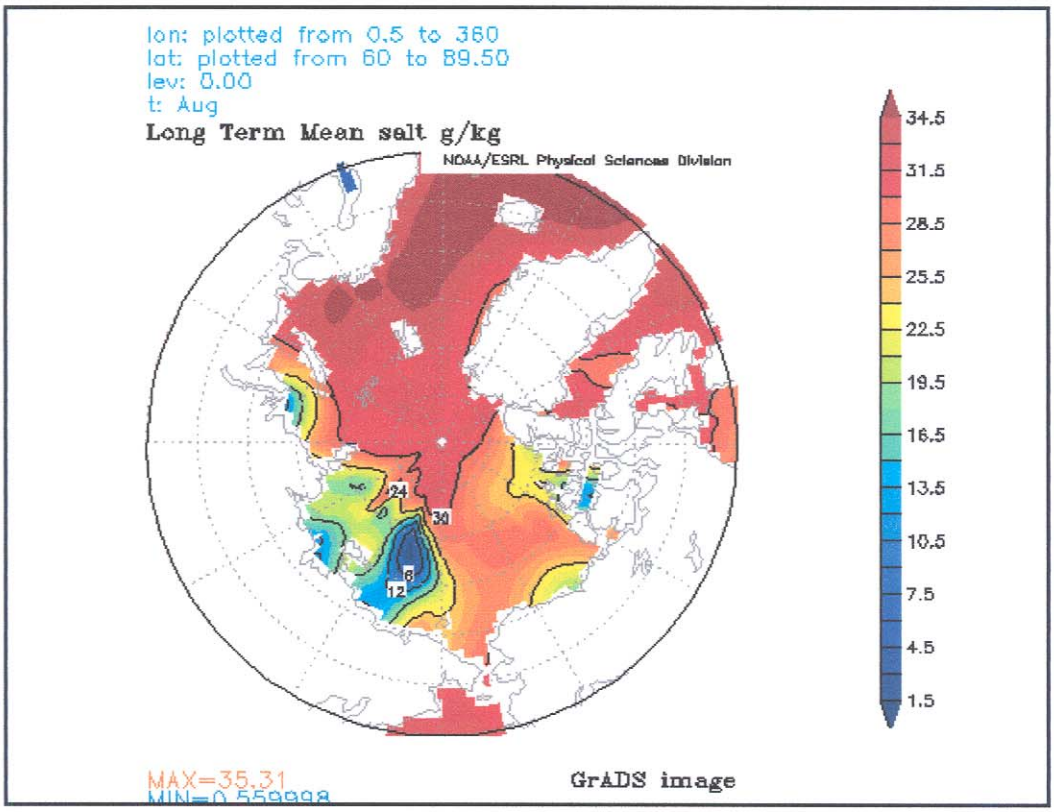

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Mar
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
30
30
42.5
37.5
32.5
27.5
22.5
17.5
12.5
7.5
MAX=43.02
GrADS image

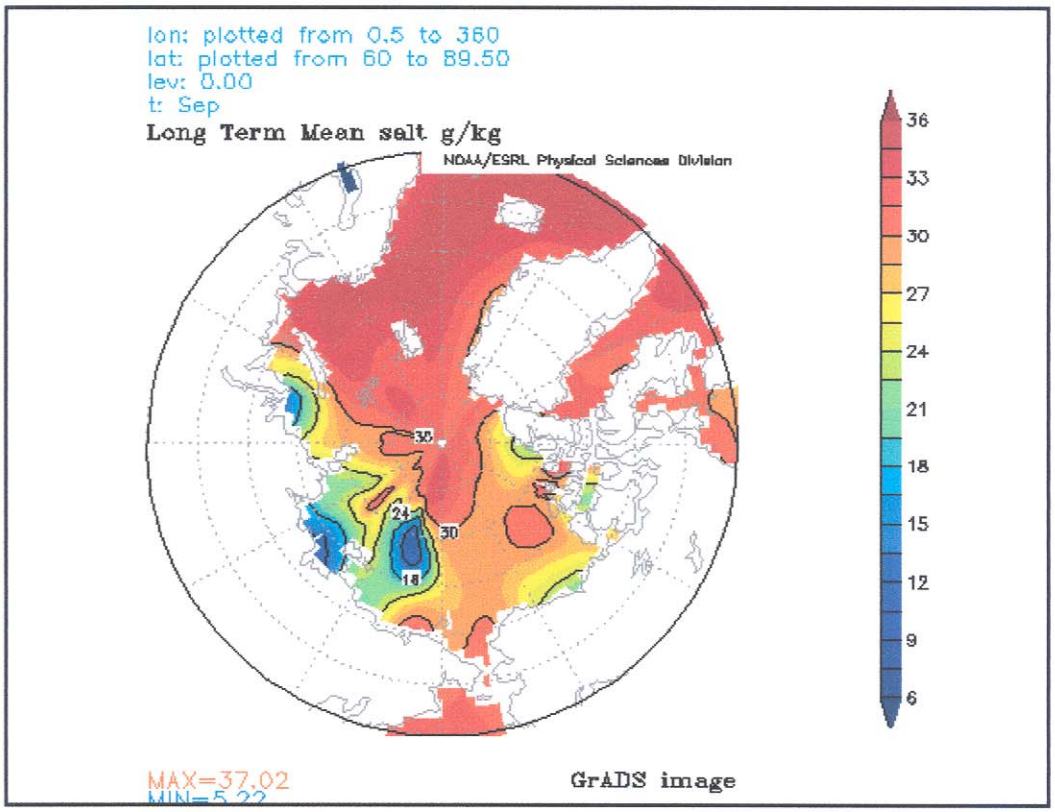

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Apr
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
30
20
42.5
37.5
32.5
27.5
22.5
17.5
12.5
7.5
2.5
MAX=47.37
GrADS image

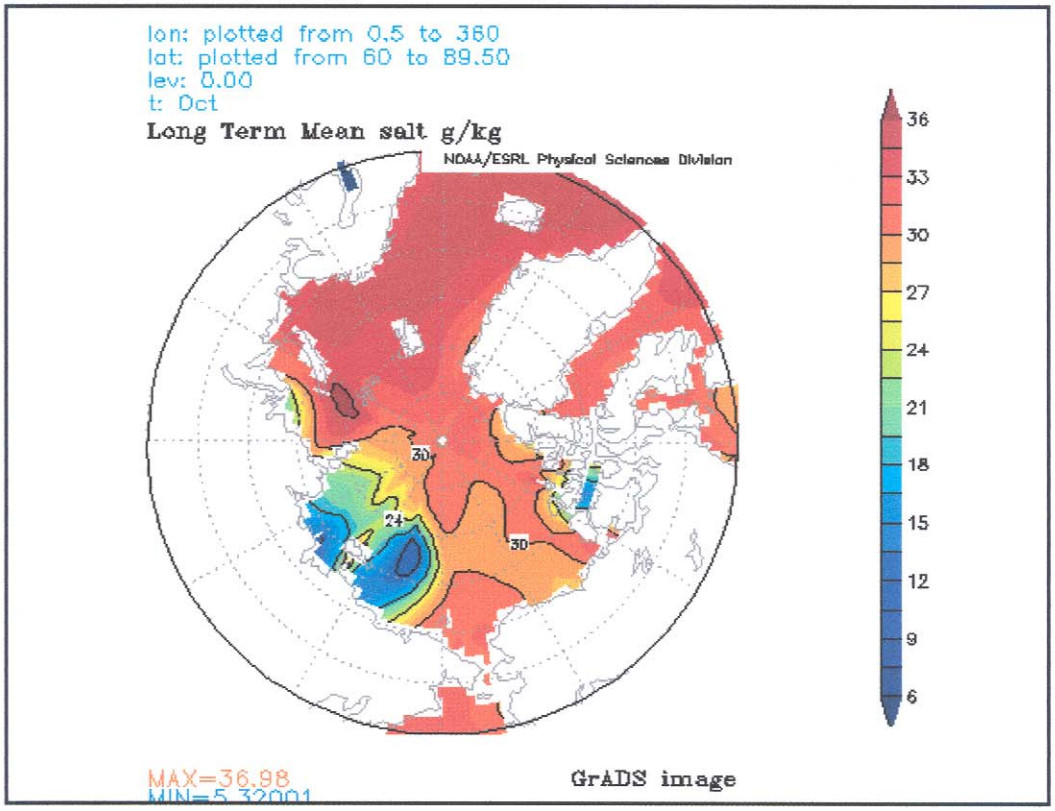

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: May
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
42.5
37.5
32.5
27.5
22.5
17.5
12.5
7.5
2.5
30
20
MAX=44.01
MIN=0.900024
GrADS image

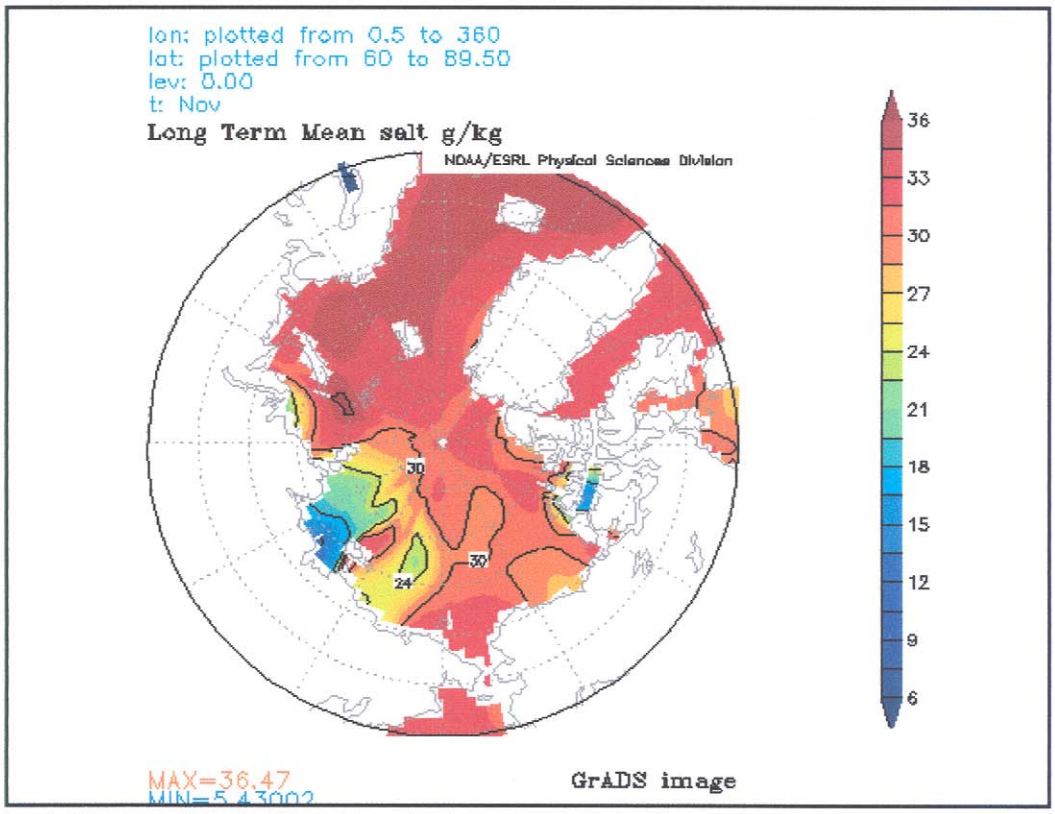

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Jun
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
40
35
30
25
20
15
10
5
0
30
20
30
30
MAX=44.01
MIN=0
GrADS image

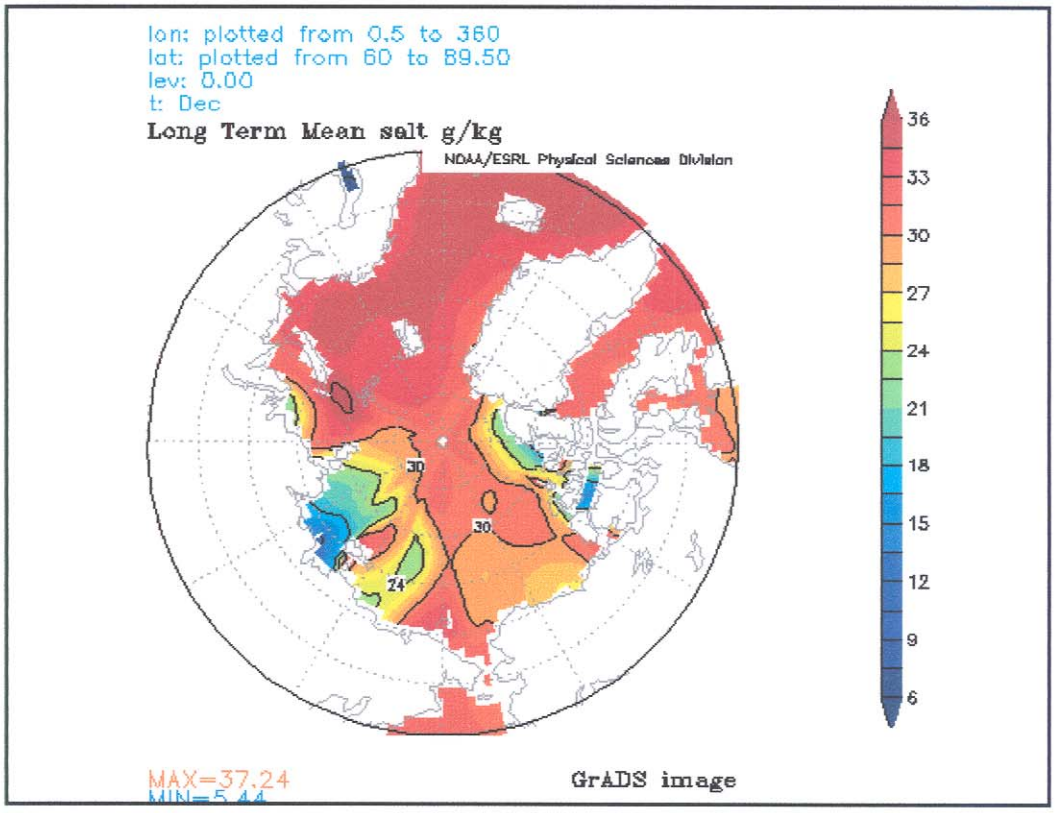

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Jul
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
34.5
31.5
28.5
25.5
22.5
19.5
16.5
13.5
10.5
7.5
4.5
1.5
30
18
24
30
24
6
12
MAX=35.34
MIN=1.31
GrADS image


lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Aug
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
34.5
31.5
28.5
25.5
22.5
19.5
16.5
13.5
10.5
7.5
4.5
1.5
24
30
6
12
MAX=35.31
MIN=0.559998
GrADS image

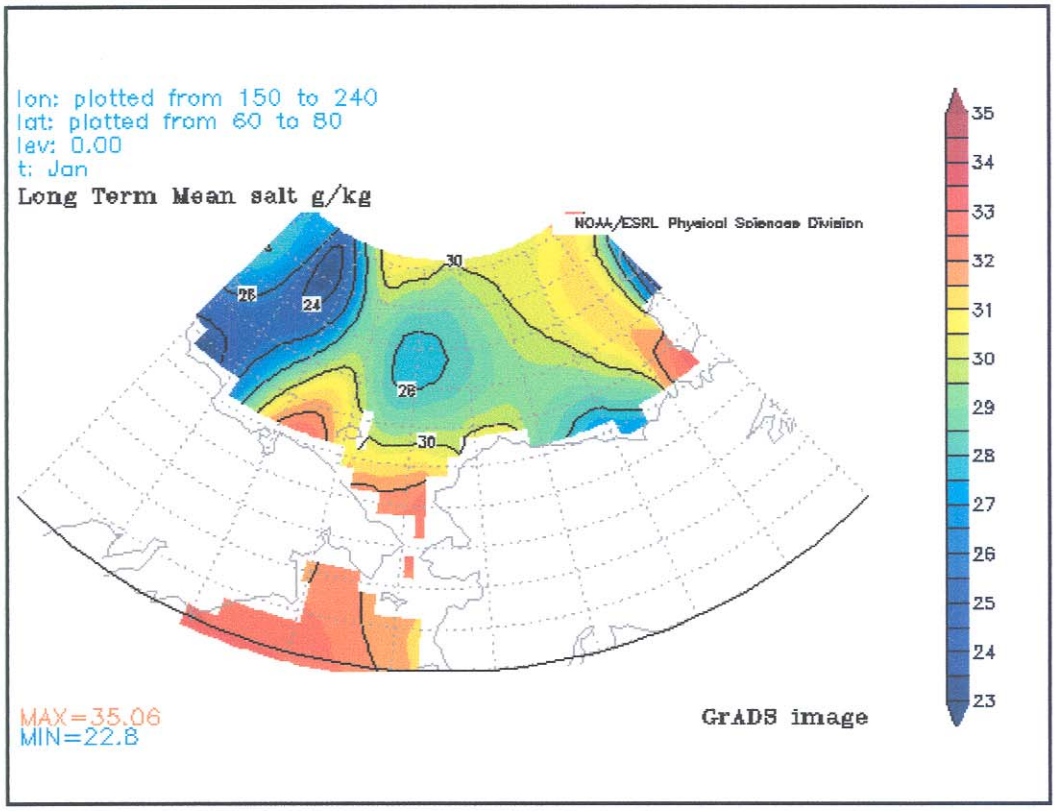

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Sep
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
36
33
30
27
24
21
18
15
12
9
6
MAX=37.02
GrADS image

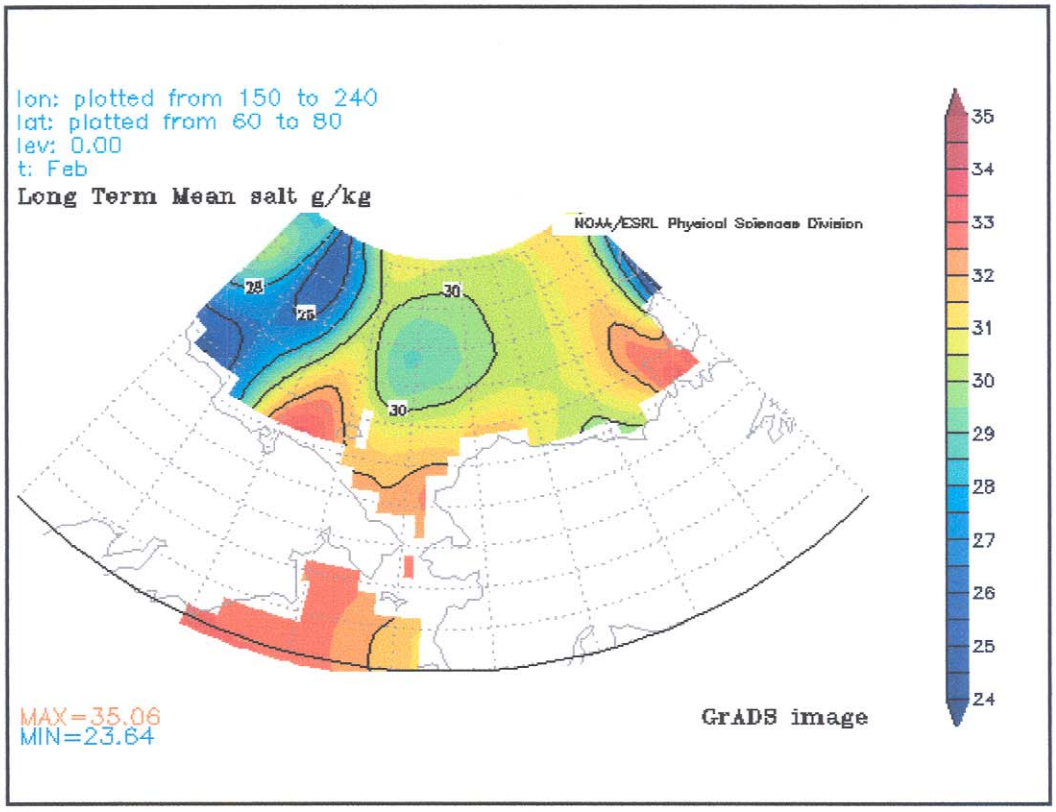

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Oct
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
36
33
30
27
24
21
18
15
12
9
6
MAX=36.98
GrADS image

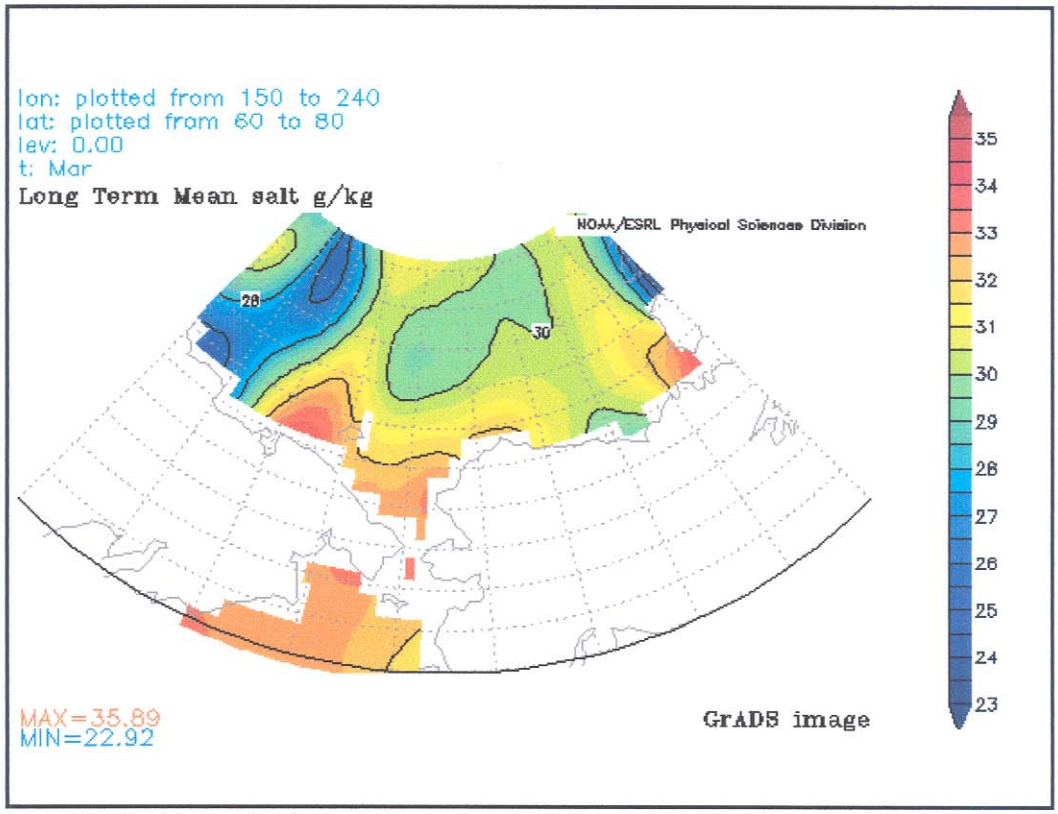

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Nov
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
36
33
30
27
24
21
18
15
12
9
6
30
30
24
MAX=36.47
GrADS image

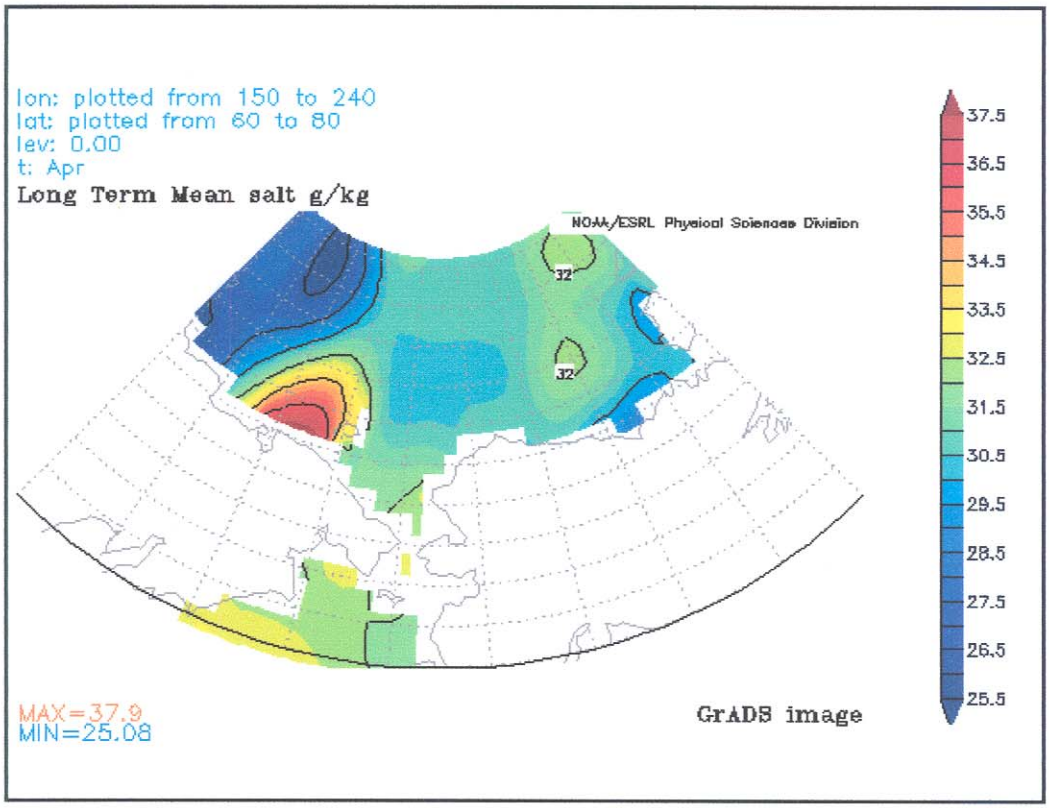

lon: plotted from 0.5 to 360
lat: plotted from 60 to 89.50
lev: 0.00
t: Dec
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
36
33
30
27
24
21
18
15
12
9
6
30
30
24
MAX=37.24
GrADS image

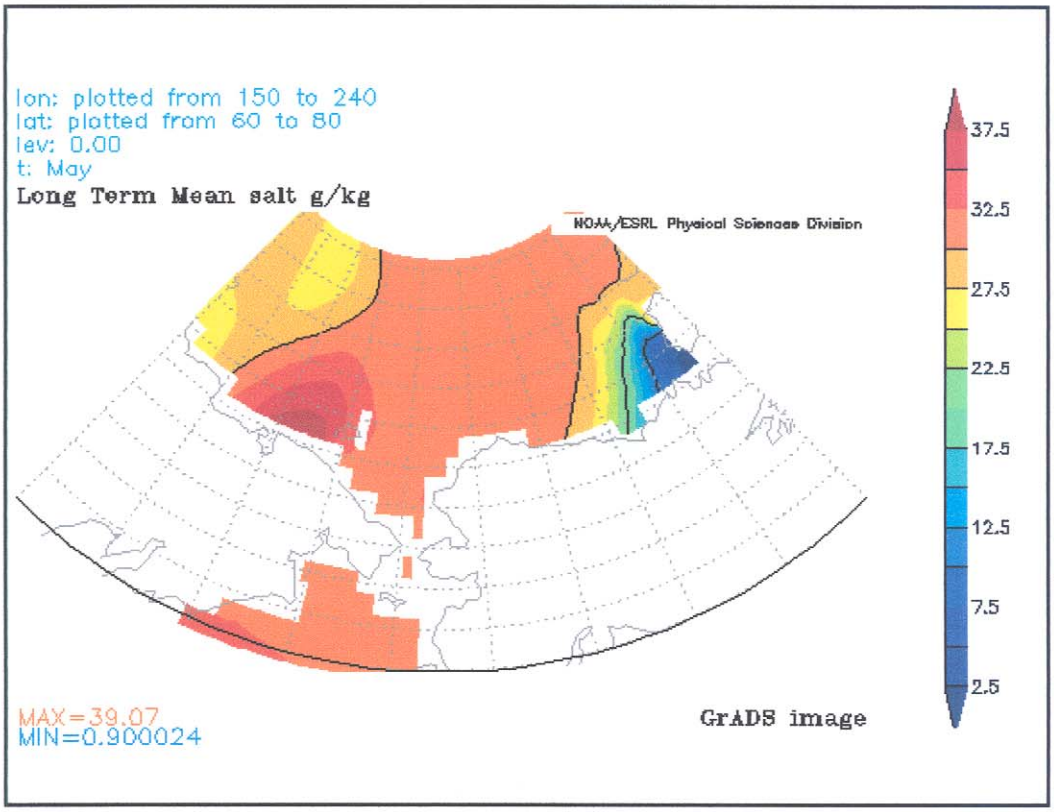
Monthly Isosalinity Maps: Chukchi Sea
(Levitus) World Ocean Atlas, 1994

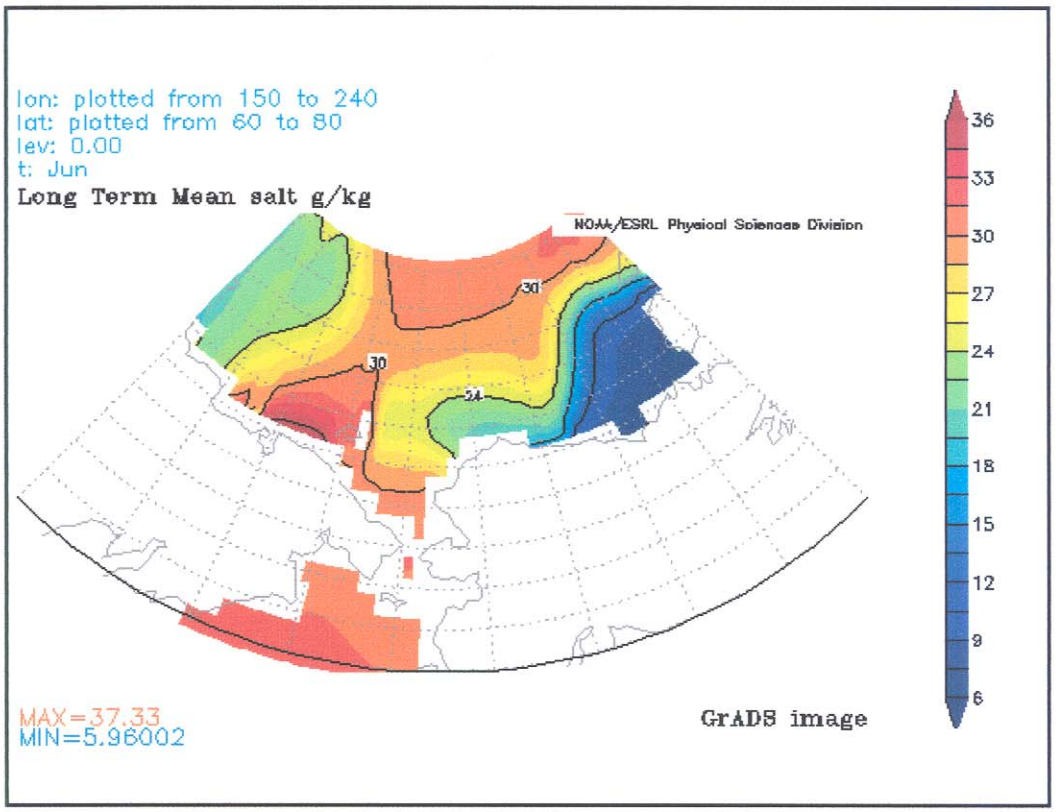

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Jan
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
30
28
24
26
30
MAX=35.06
MIN=22.8
GrADS image
35
34
33
32
31
30
29
28
27
26
25
24
23

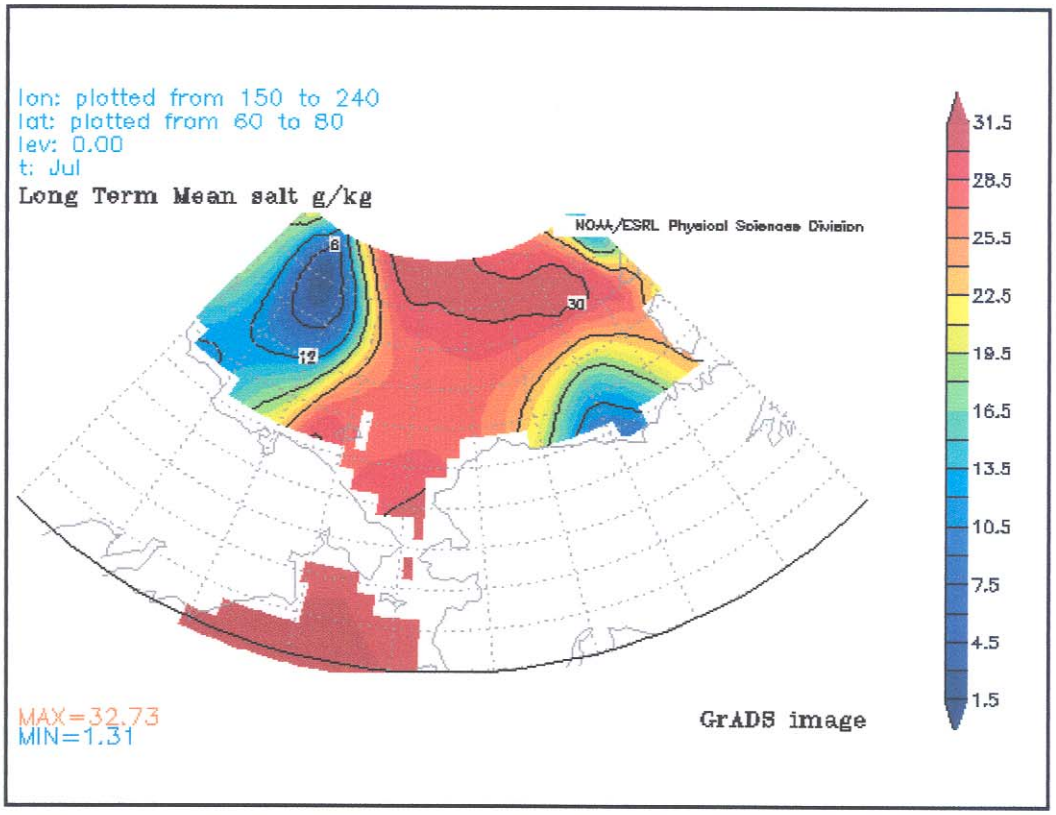

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Feb
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
28
26
30
30
MAX=35.06
MIN=23.64
GrADS image
35
34
33
32
31
30
29
28
27
26
25
24

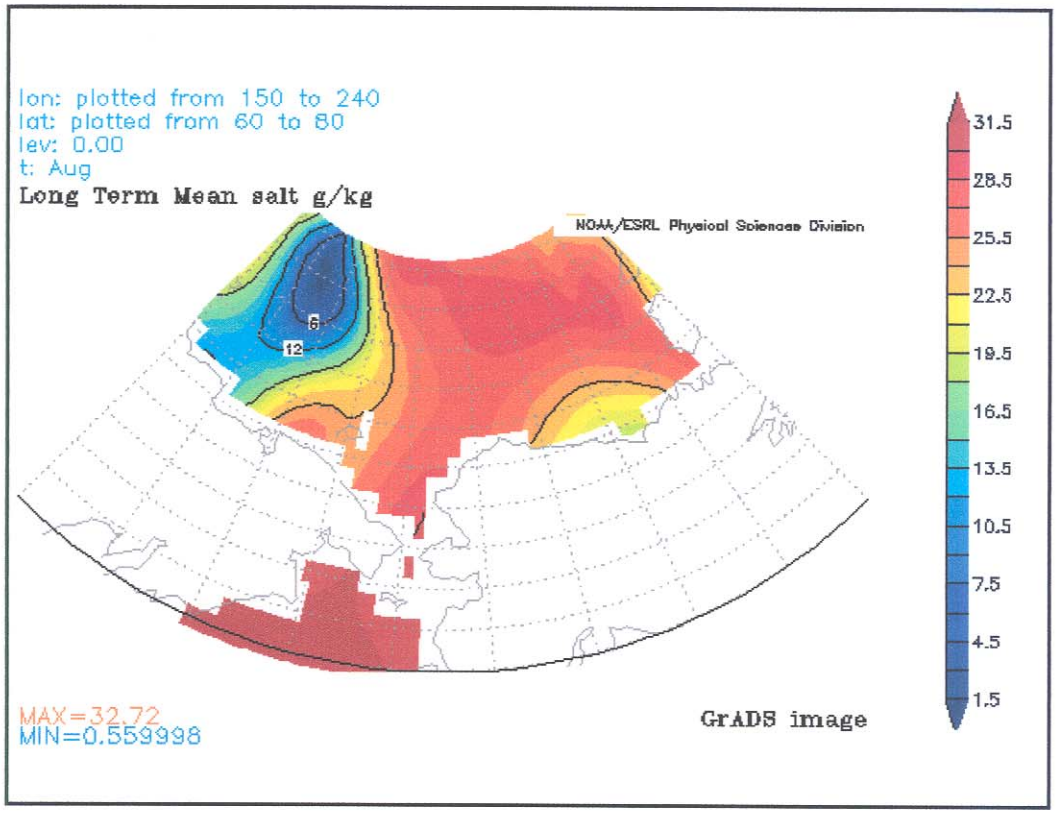

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Mar
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
28
30
35
34
33
32
31
30
29
28
27
26
25
24
23
MAX=35.89
MIN=22.92
GrADS image

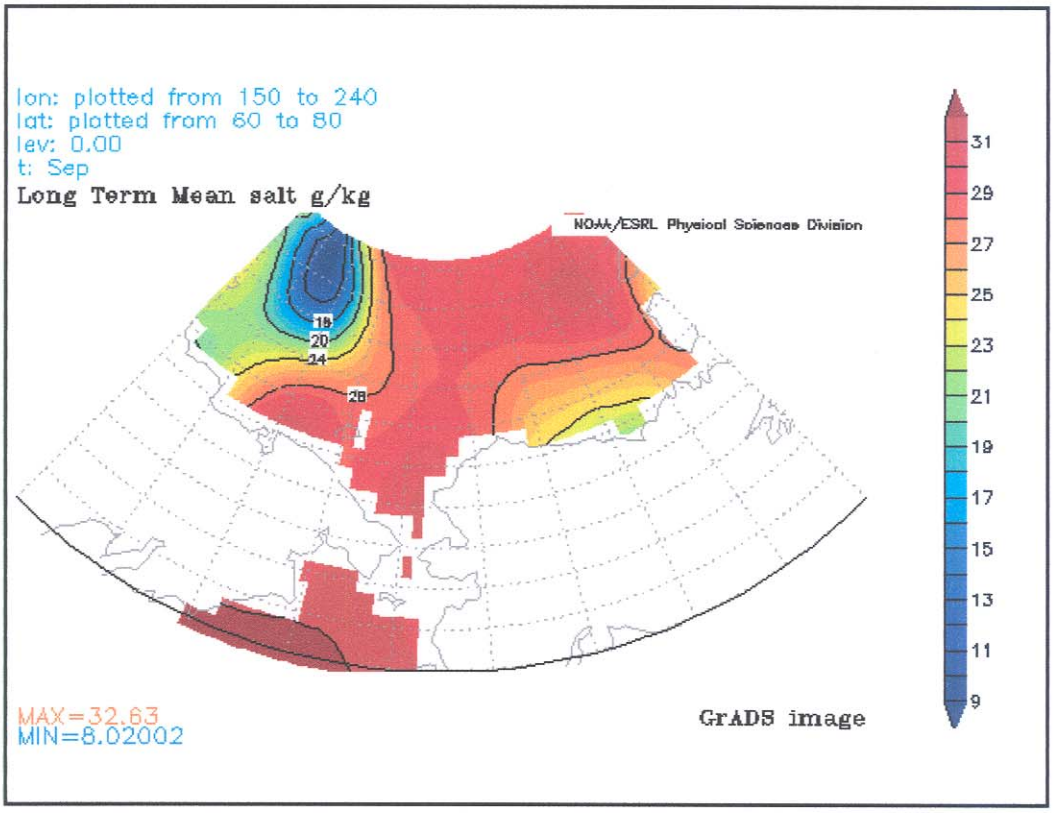

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Apr
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32
32
37.5
36.5
35.5
34.5
33.5
32.5
31.5
30.5
29.5
28.5
27.5
26.5
25.5
MAX=37.9
MIN=25.08
GrADS image

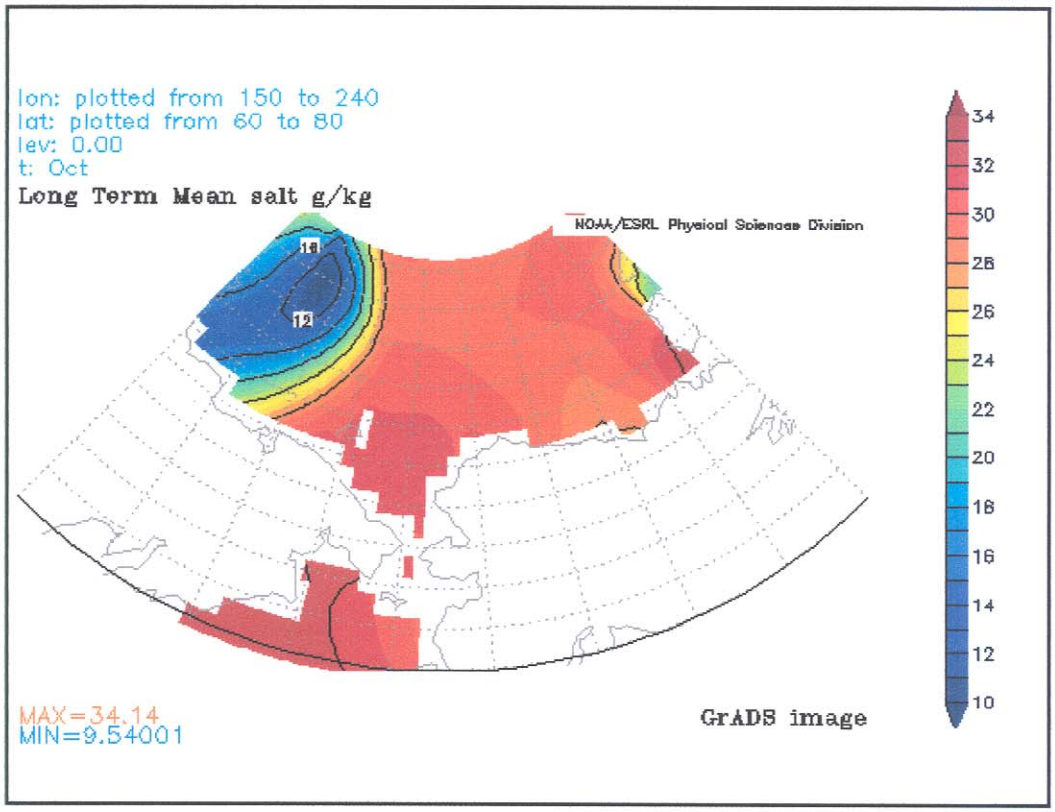

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: May
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
37.5
32.5
27.5
22.5
17.5
12.5
7.5
2.5
MAX=39.07
MIN=0.900024
GrADS image

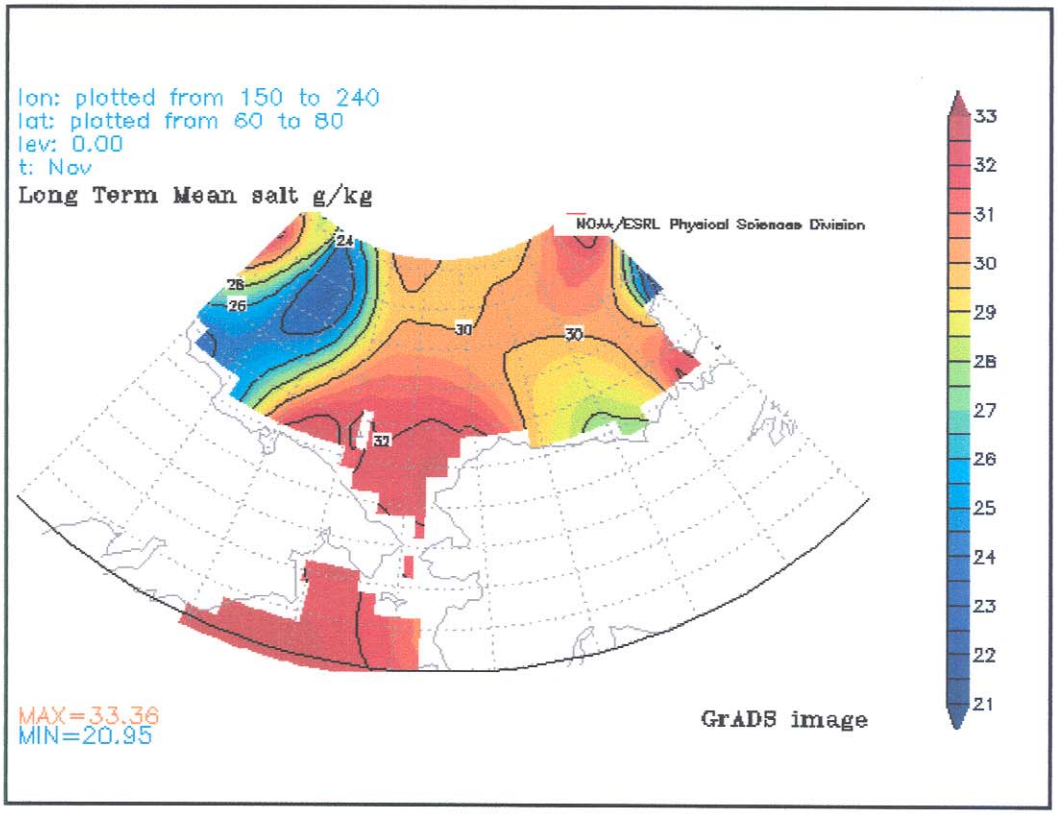

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Jun
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
30
30
24
36
33
30
27
24
21
18
15
12
9
6
MAX=37.33
MIN=5.96002
GrADS image

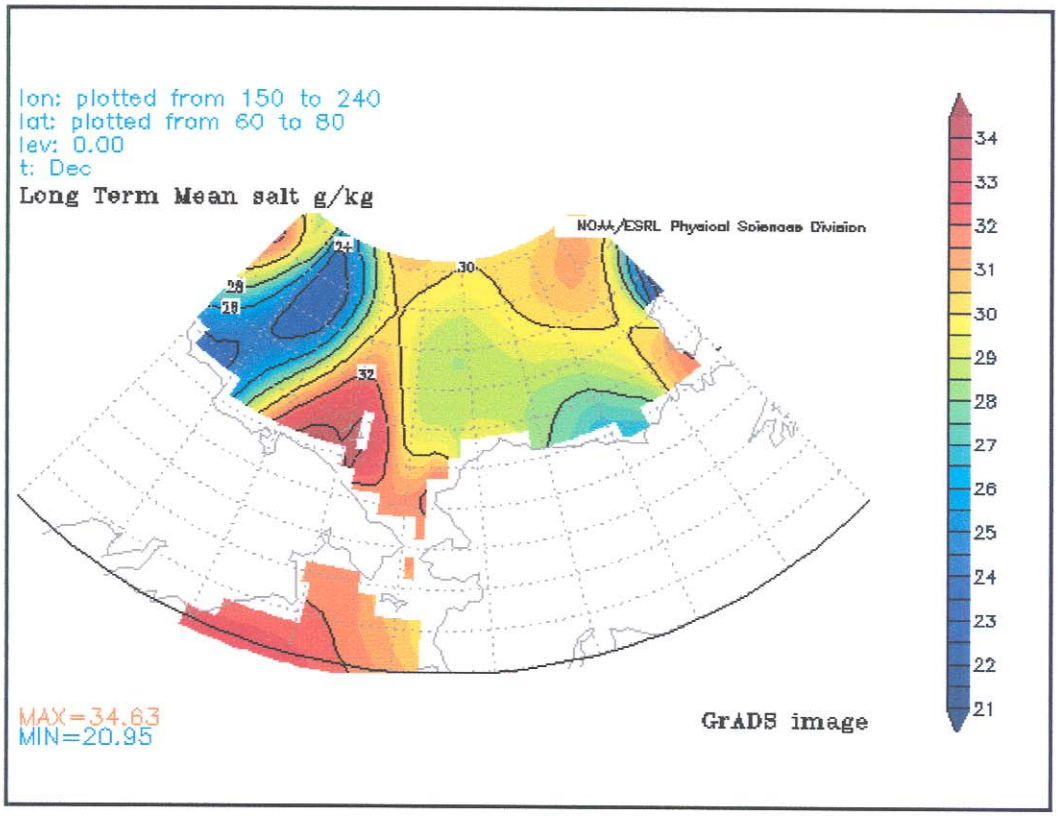

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Jul
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
6
12
30
31.5
28.5
25.5
22.5
19.5
16.5
13.5
10.5
7.5
4.5
1.5
MAX=32.73
MIN=1.31
GrADS image


lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Aug
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
6
12
31.5
28.5
25.5
22.5
19.5
16.5
13.5
10.5
7.5
4.5
1.5
MAX=32.72
MIN=0.559998
GrADS image

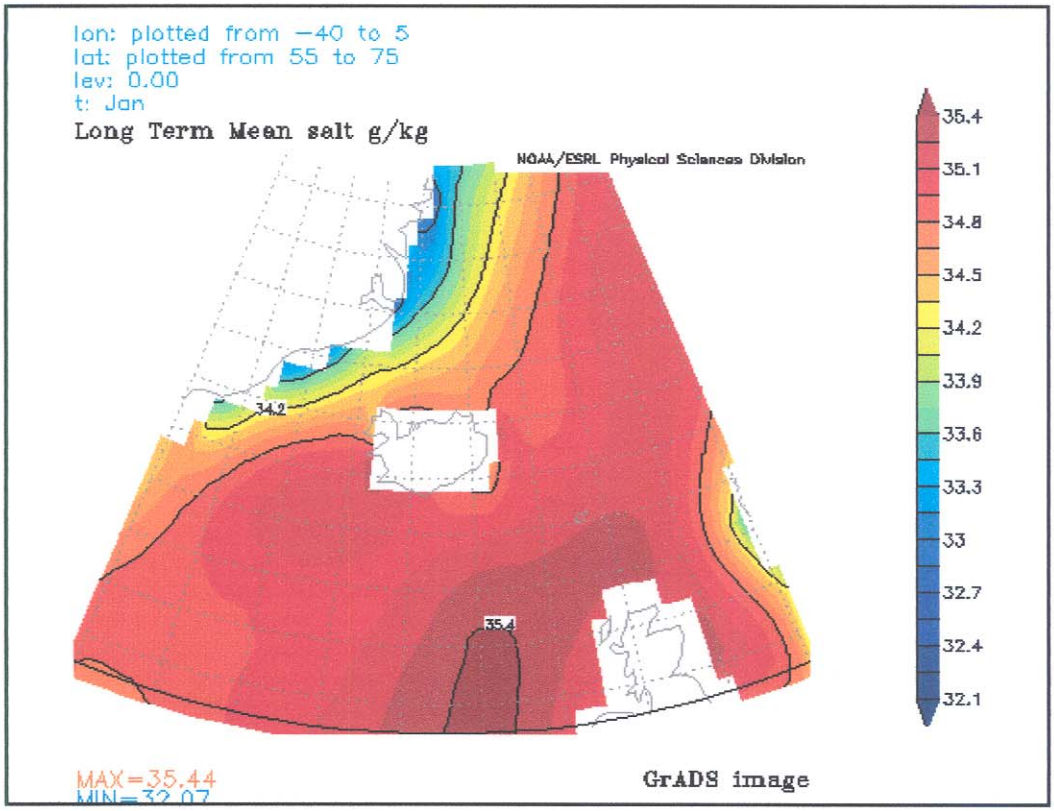

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Sep
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
16
20
24
28
31
29
27
25
23
21
19
17
15
13
11
9
MAX=32.63
MIN=8.02002
GrADS image

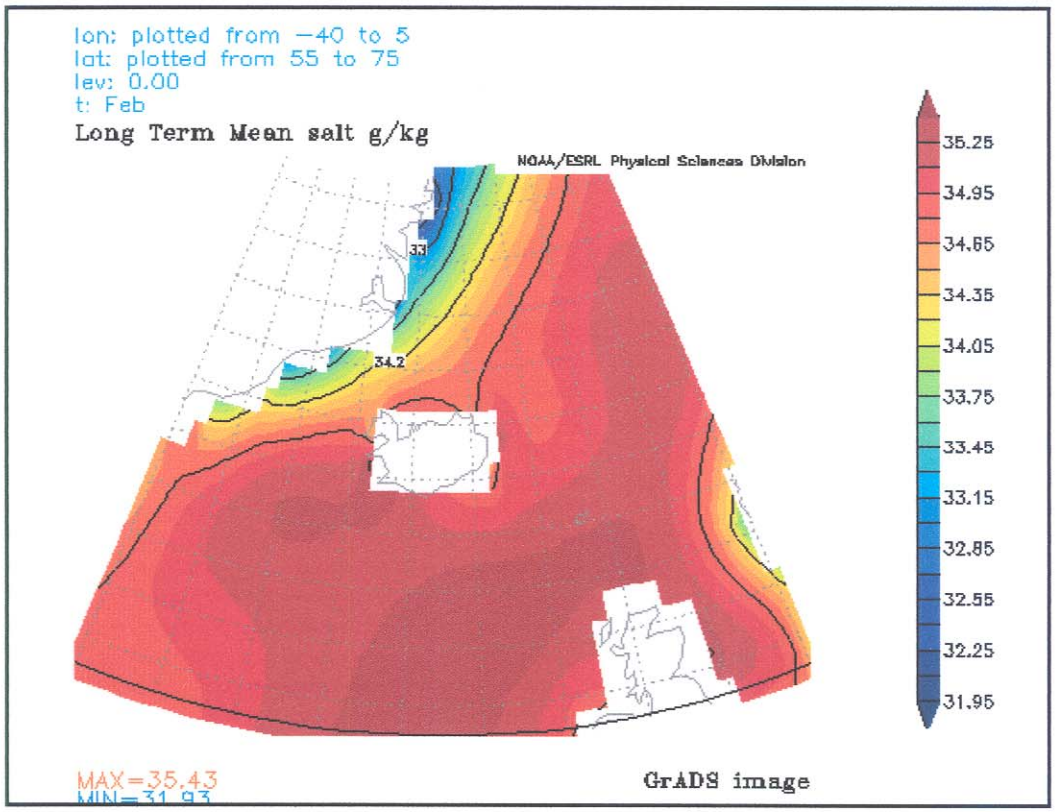

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Oct
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
14
12
34
32
30
28
26
24
22
20
18
16
14
12
10
MAX=34.14
MIN=9.54001
GrADS image

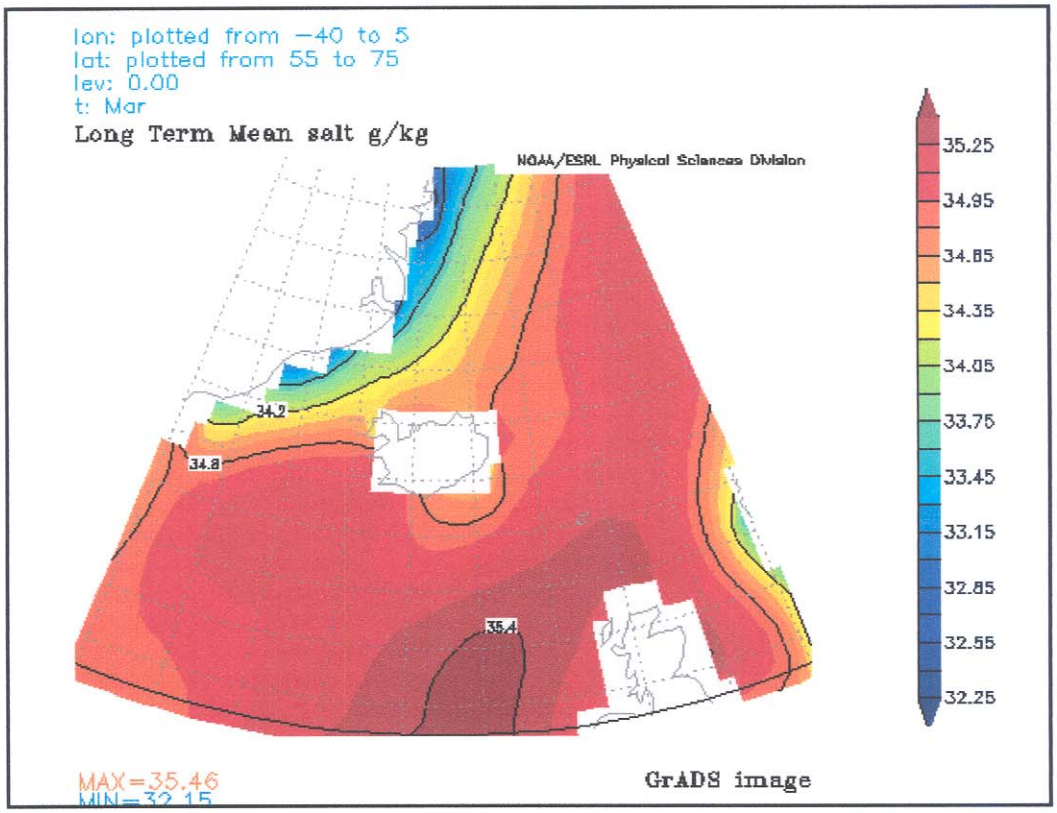

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Nov
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
24
26
28
30
32
33
32
31
30
29
28
27
26
25
24
23
22
21
MAX=33.36
MIN=20.95
GrADS image

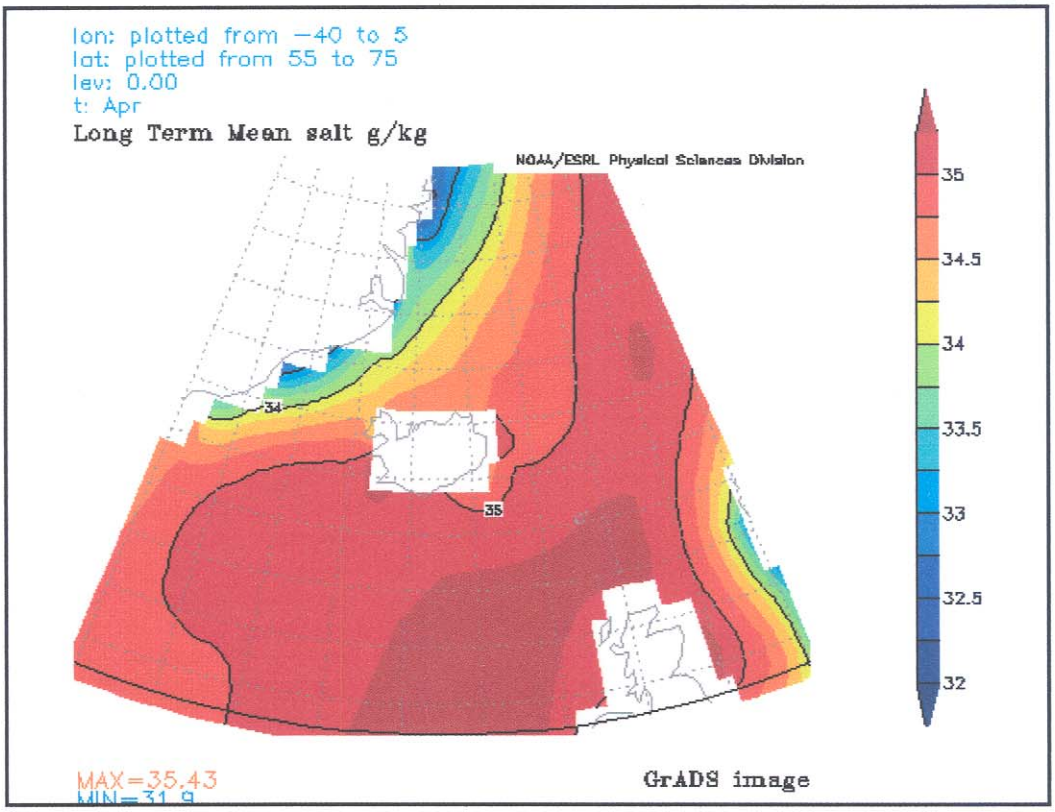

lon: plotted from 150 to 240
lat: plotted from 60 to 80
lev: 0.00
t: Dec
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
24
26
28
30
32
34
33
32
31
30
29
28
27
26
25
24
23
22
21
MAX=34.63
MIN=20.95
GrADS image

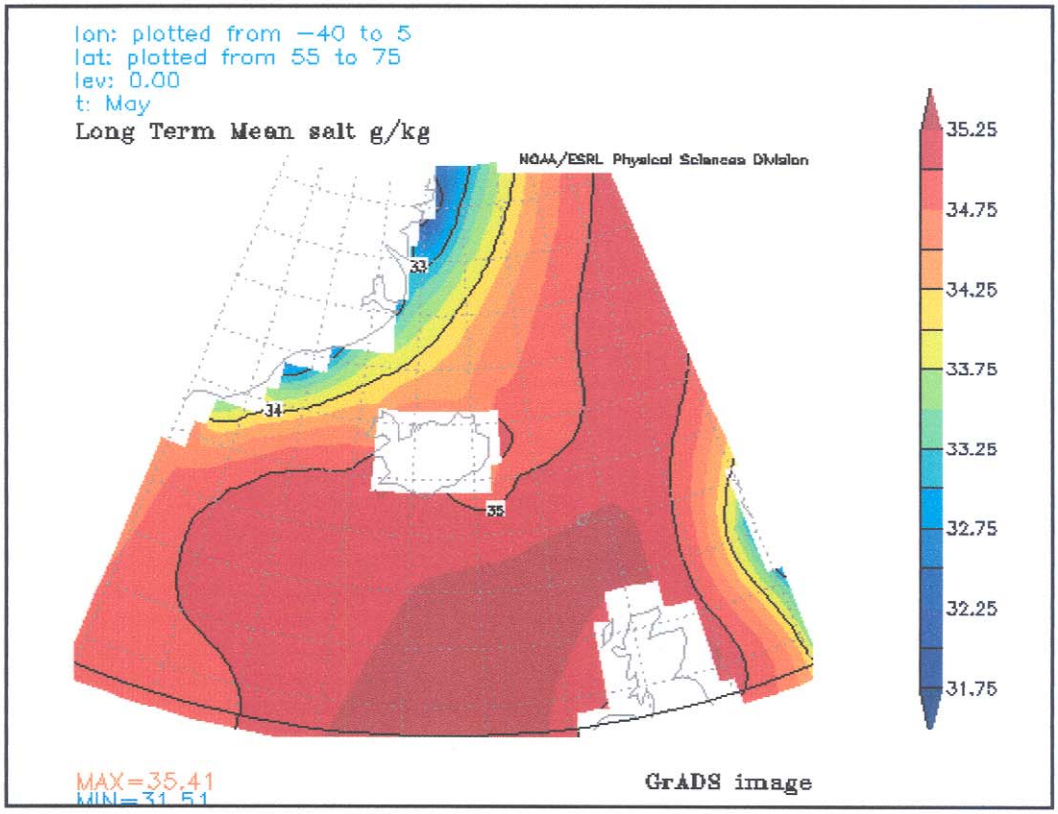
Monthly Isosalinity Maps: Iceland
(Levitus) World Ocean Atlas, 1994

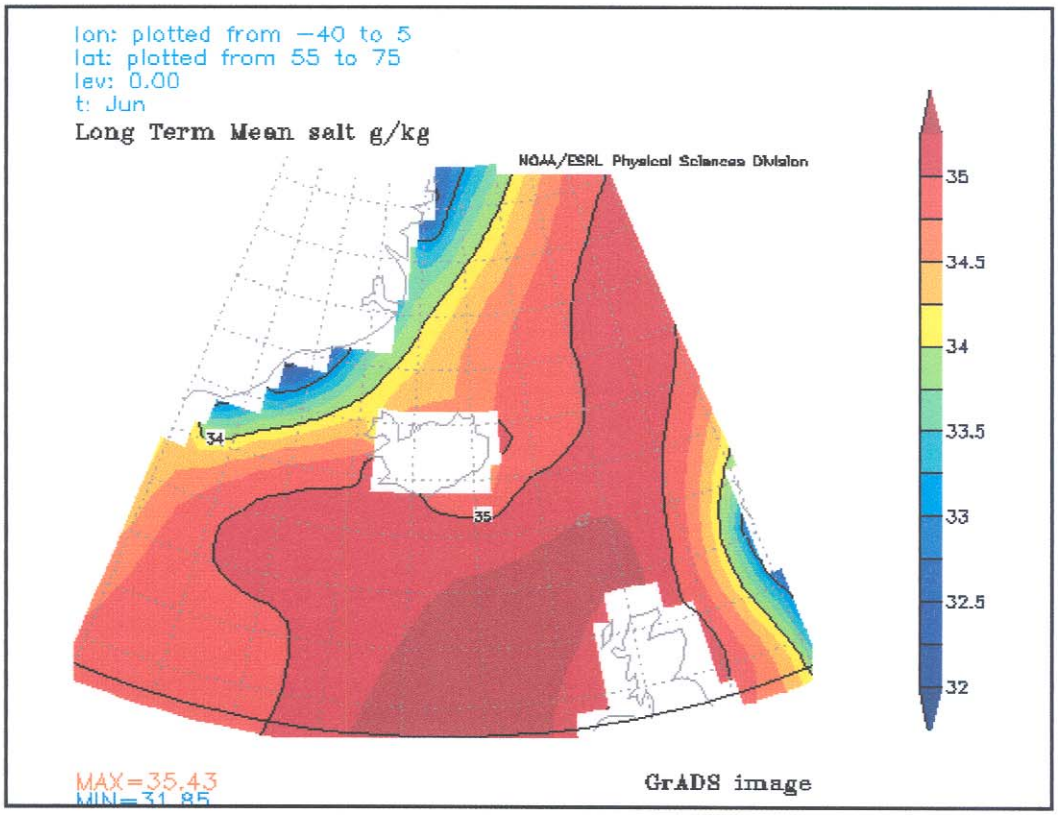

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Jan
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
34.2
35.4
35.4
35.1
34.8
34.5
34.2
33.9
33.6
33.3
33
32.7
32.4
32.1
MAX=35.44
MIN=32.07
GrADS image

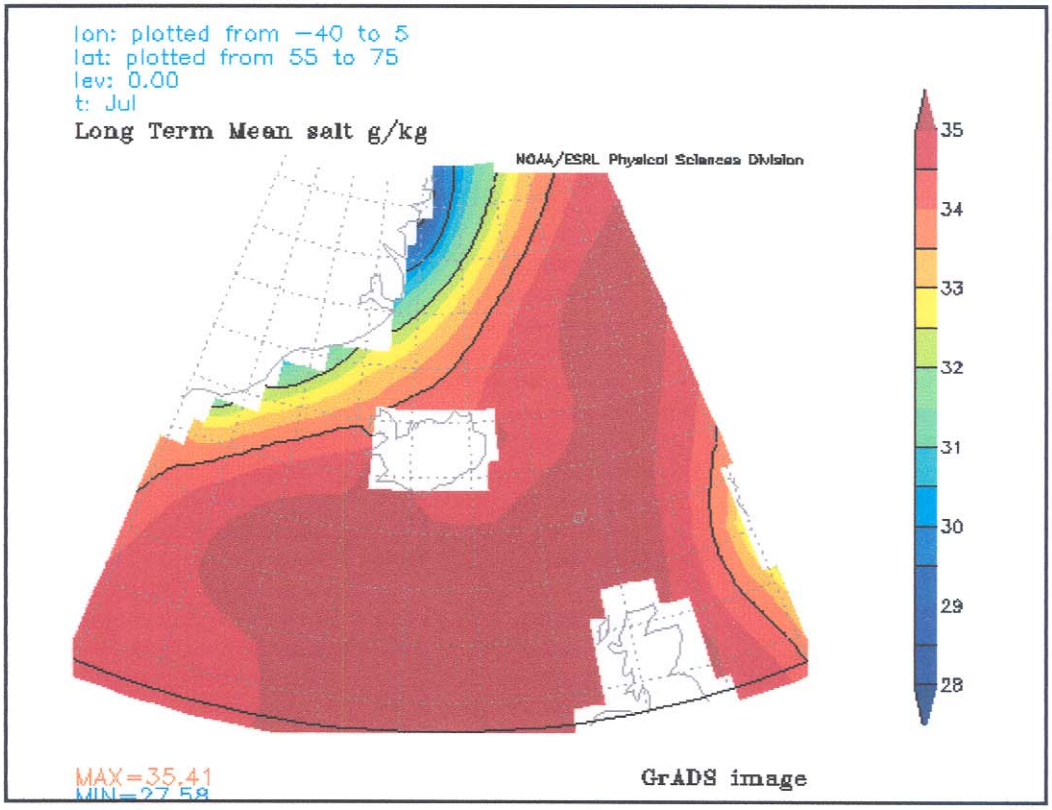

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Feb
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
33
34.2
35.25
34.95
34.65
34.35
34.05
33.75
33.45
33.15
32.85
32.55
32.25
31.95
MAX=35.43
MIN=31.93
GrADS image

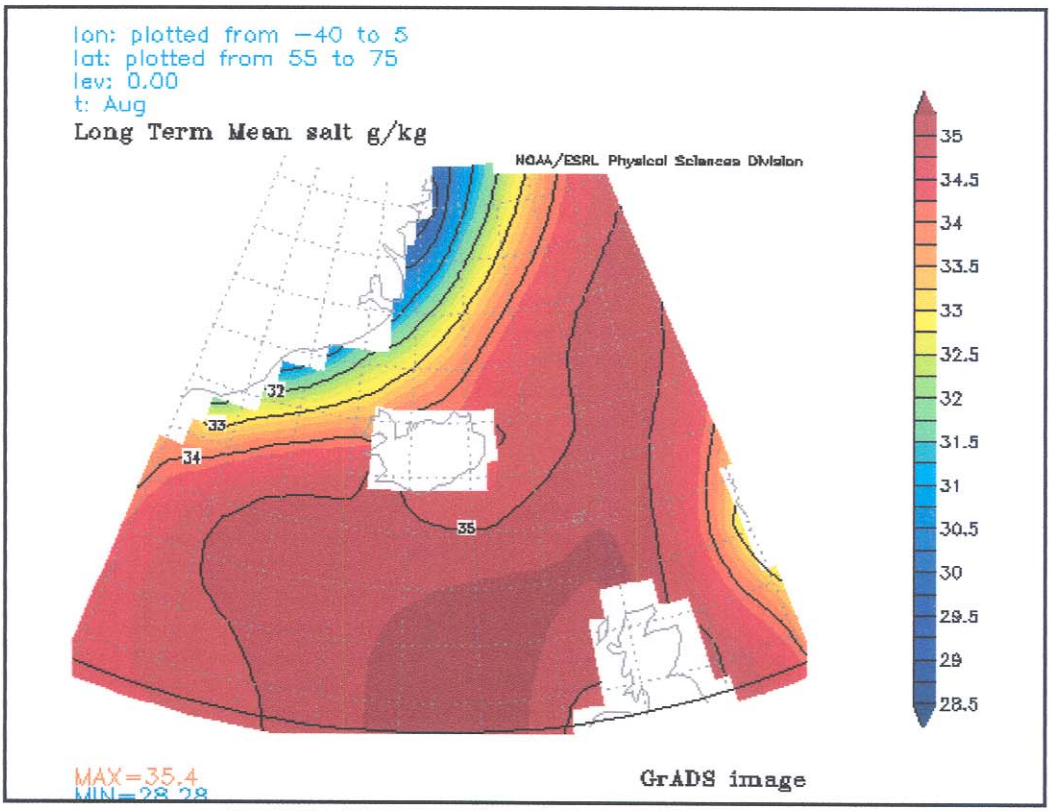

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Mar
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
34.2
34.8
35.4
35.25
34.95
34.65
34.35
34.05
33.75
33.45
33.15
32.85
32.55
32.25
MAX=35.46
MIN=32.15
GrADS image

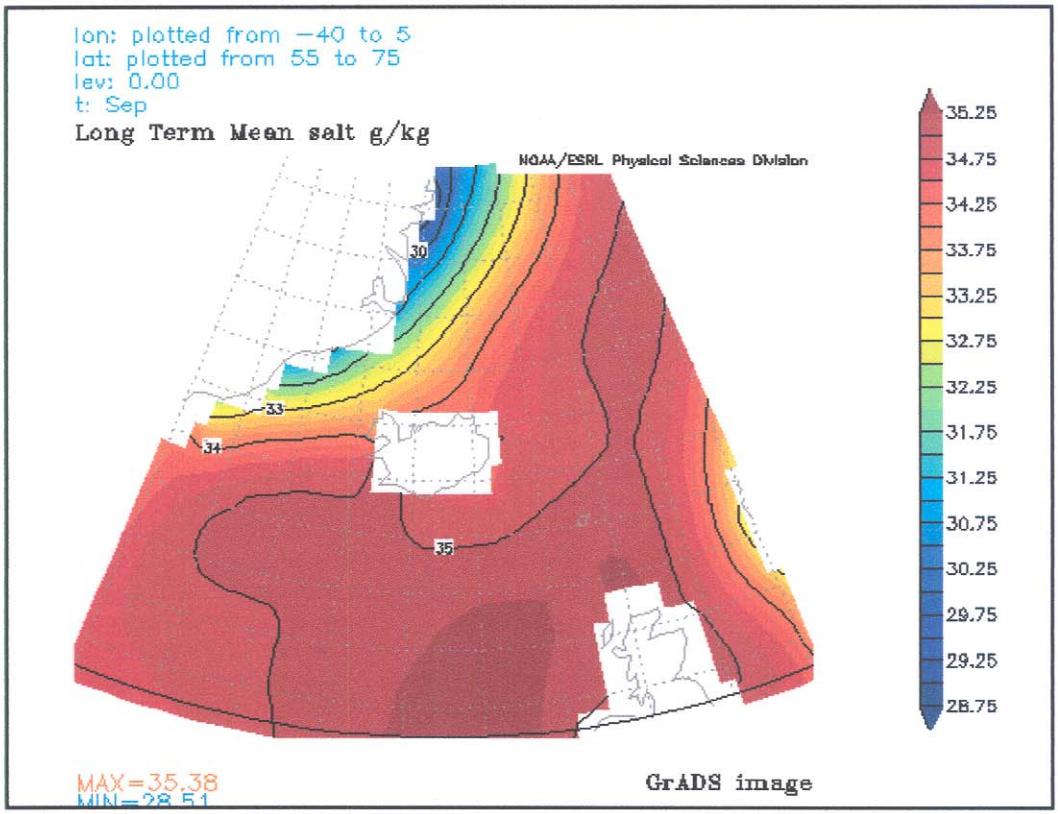

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Apr
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
34
35
35
34.5
34
33.5
33
32.5
32
MAX=35.43
MIN=31.9
GrADS image

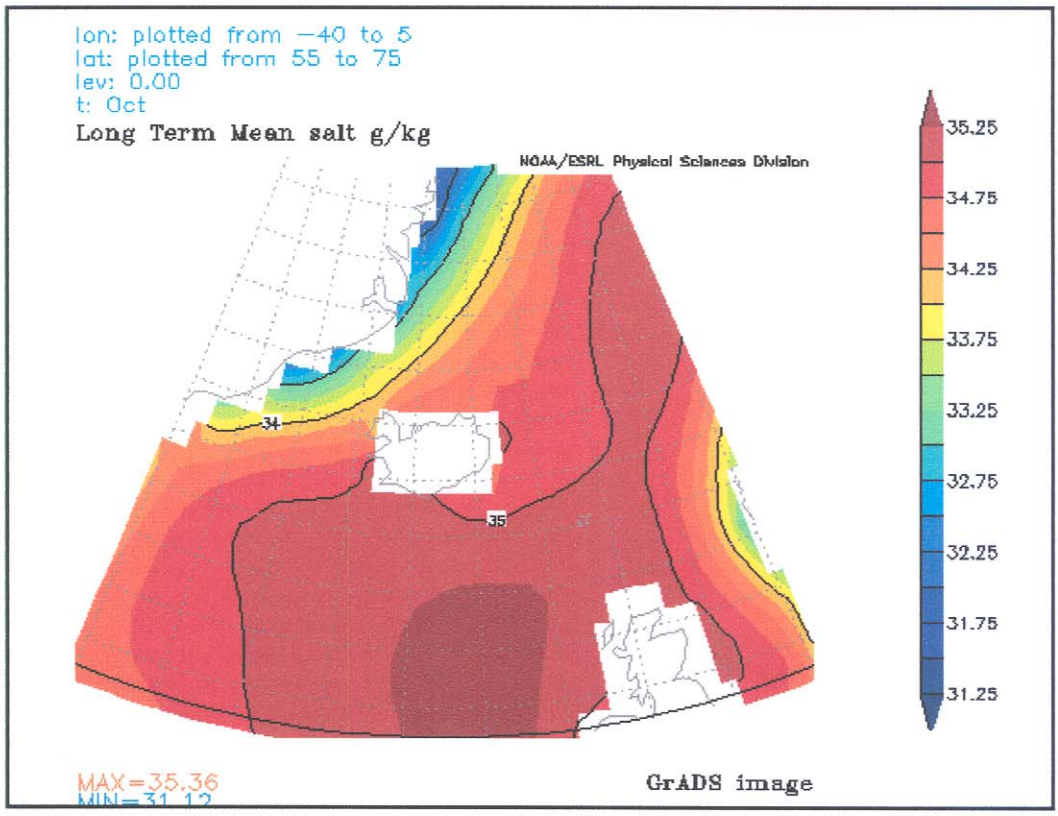

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: May
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
33
34
35
35.25
34.75
34.25
33.75
33.25
32.75
32.25
31.75
MAX=35.41
MIN=31.51
GrADS image

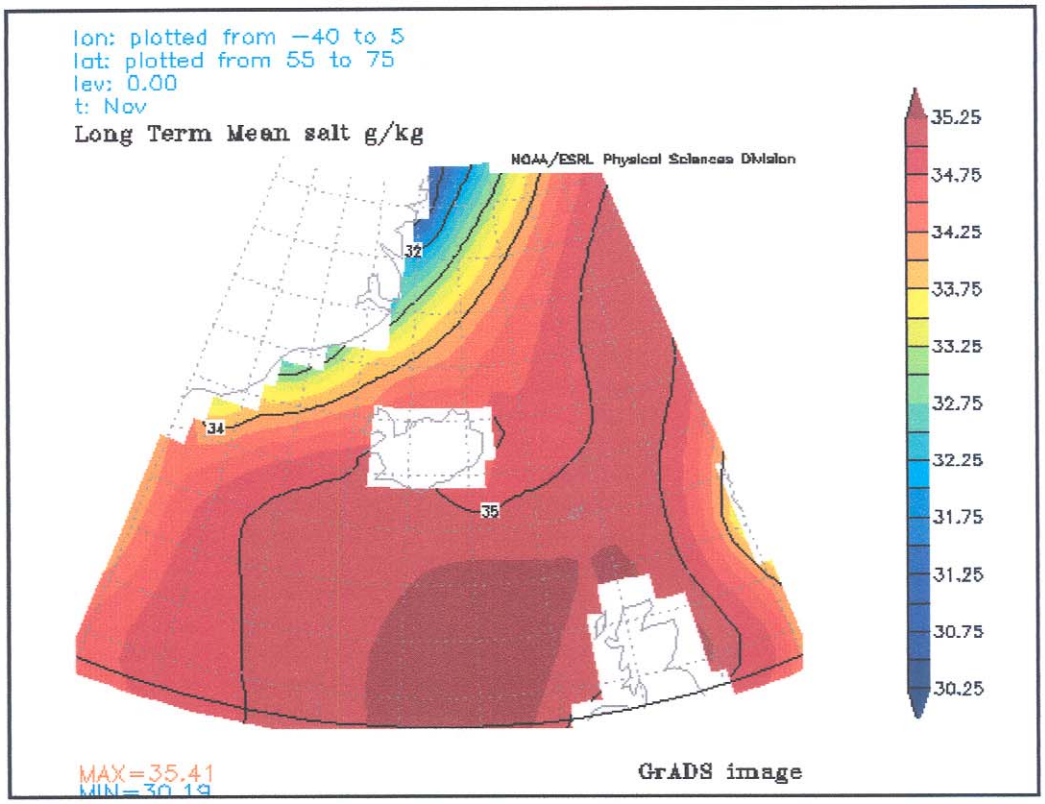

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Jun
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
34
35
35
34.5
34
33.5
33
32.5
32
MAX=35.43
MIN=31.85
GrADS image

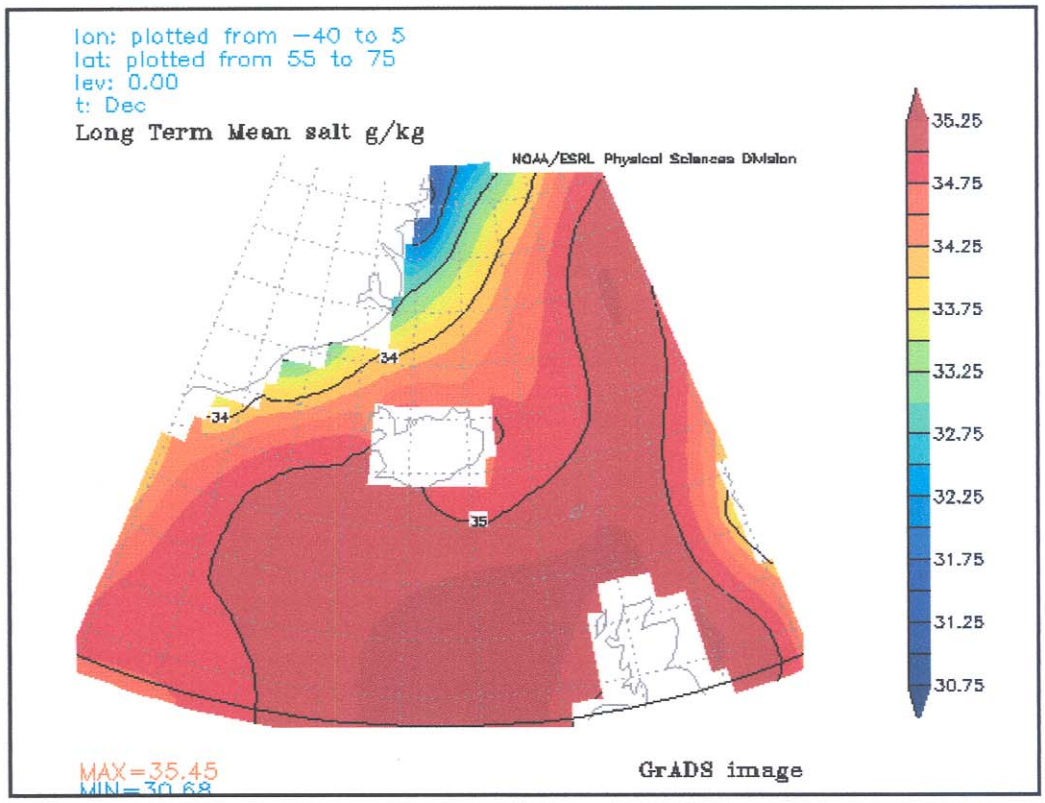

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Jul
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
35
34
33
32
31
30
29
28
MAX=35.41
GrADS image


lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Aug
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32
33
34
35
35
34.5
34
33.5
33
32.5
32
31.5
31
30.5
30
29.5
29
28.5
MAX=35.4
GrADS image

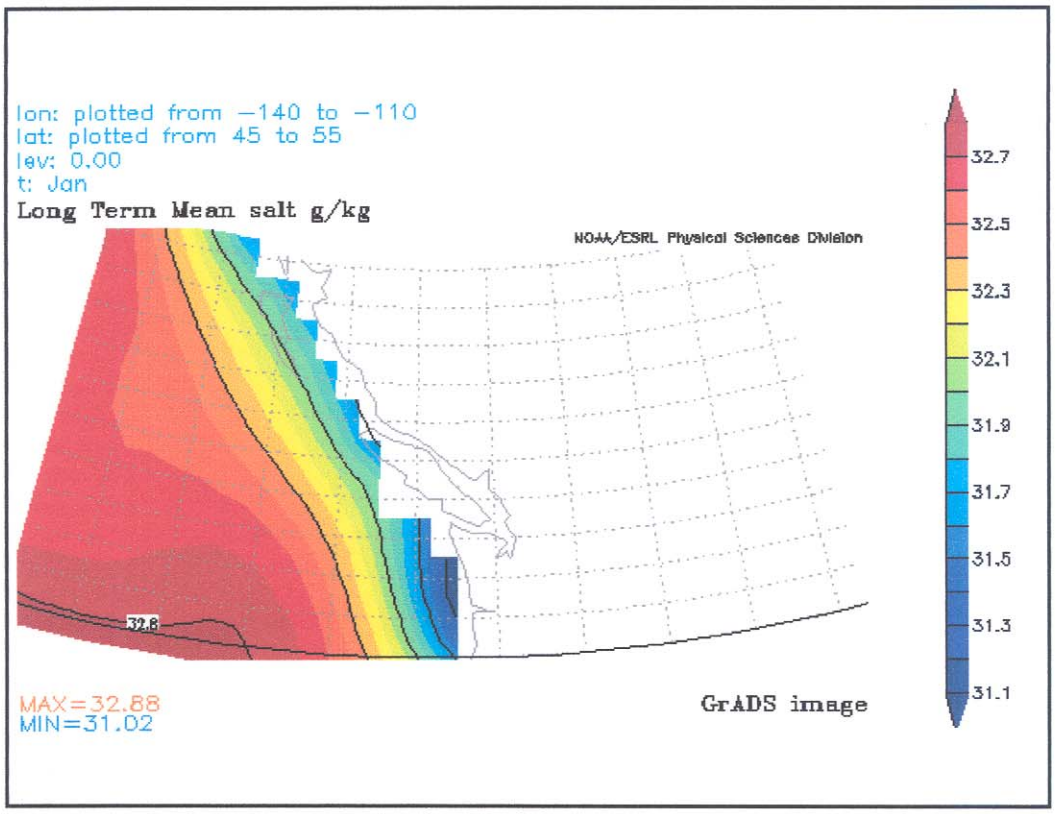

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Sep
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
30
33
34
35
35.25
34.75
34.25
33.75
33.25
32.75
32.25
31.75
31.25
30.75
30.25
29.75
29.25
28.75
MAX=35.38
MIN=28.51
GrADS image

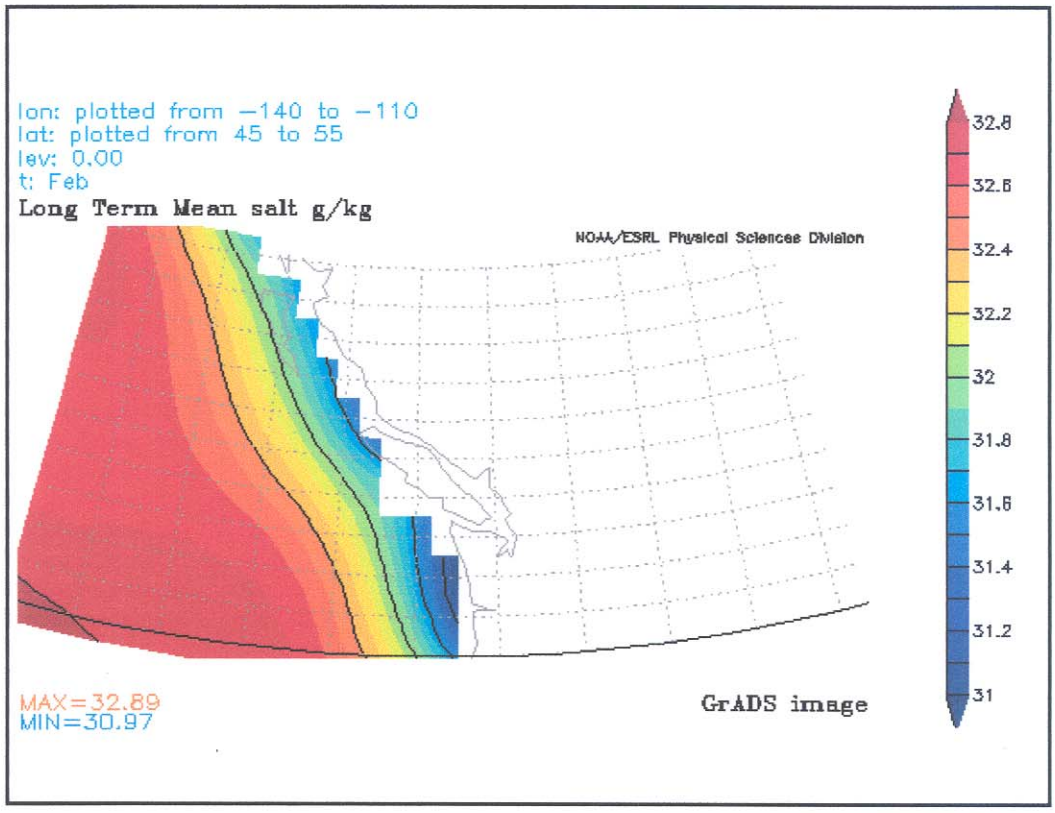

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Oct
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
34
35
35.25
34.75
34.25
33.75
33.25
32.75
32.25
31.75
31.25
MAX=35.36
MIN=31.12
GrADS image

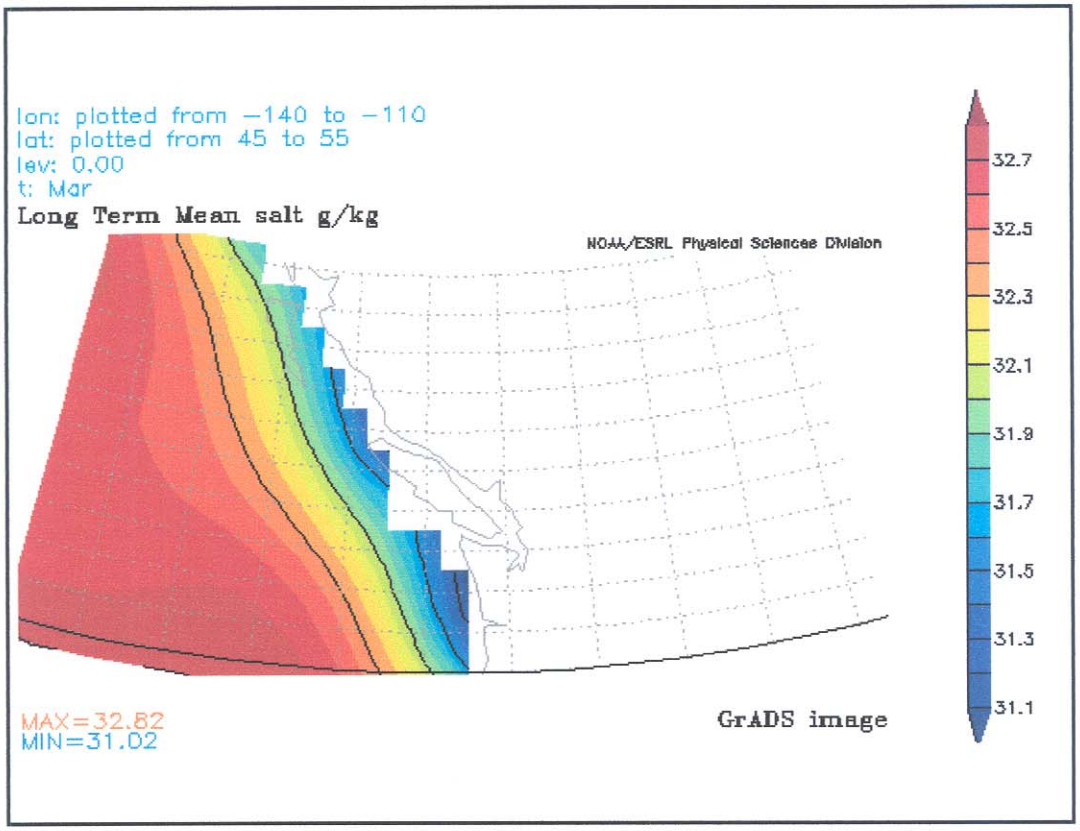

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Nov
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32
34
35
35.25
34.75
34.25
33.75
33.25
32.75
32.25
31.75
31.25
30.75
30.25
MAX=35.41
GrADS image

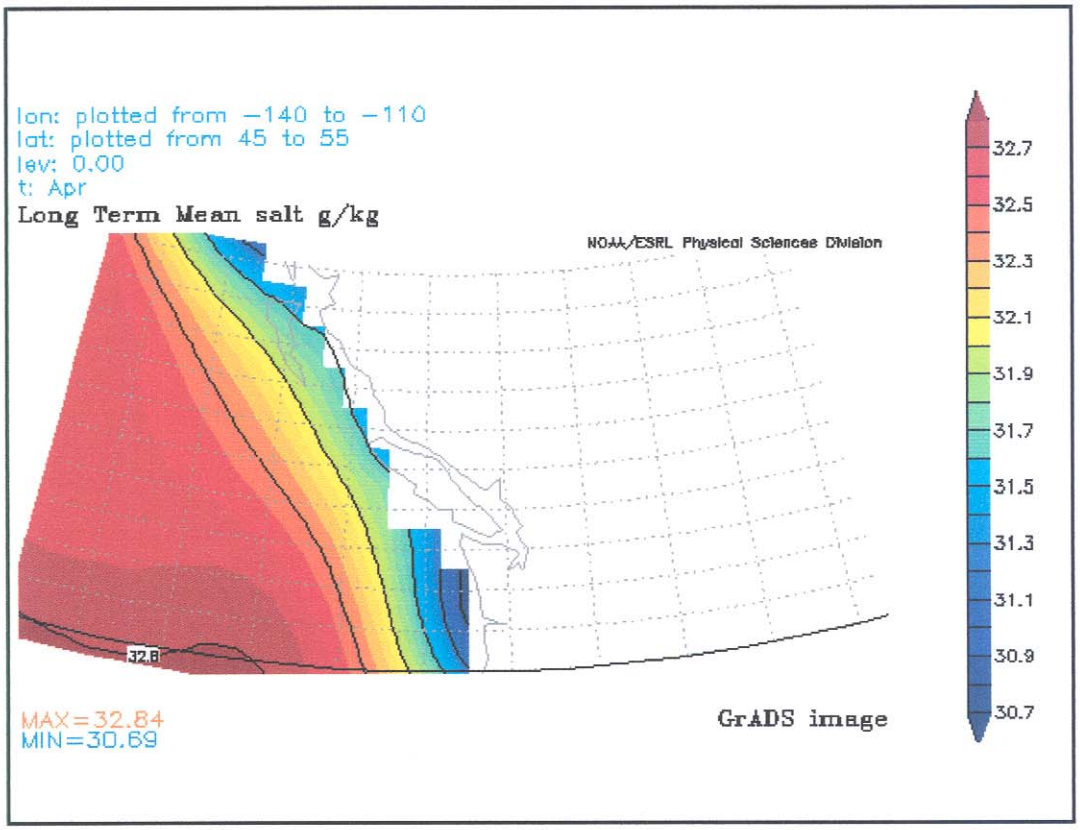

lon: plotted from −40 to 5
lat: plotted from 55 to 75
lev: 0.00
t: Dec
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
34
34
35
35.25
34.75
34.25
33.75
33.25
32.75
32.25
31.75
31.25
30.75
MAX=35.45
GrADS image

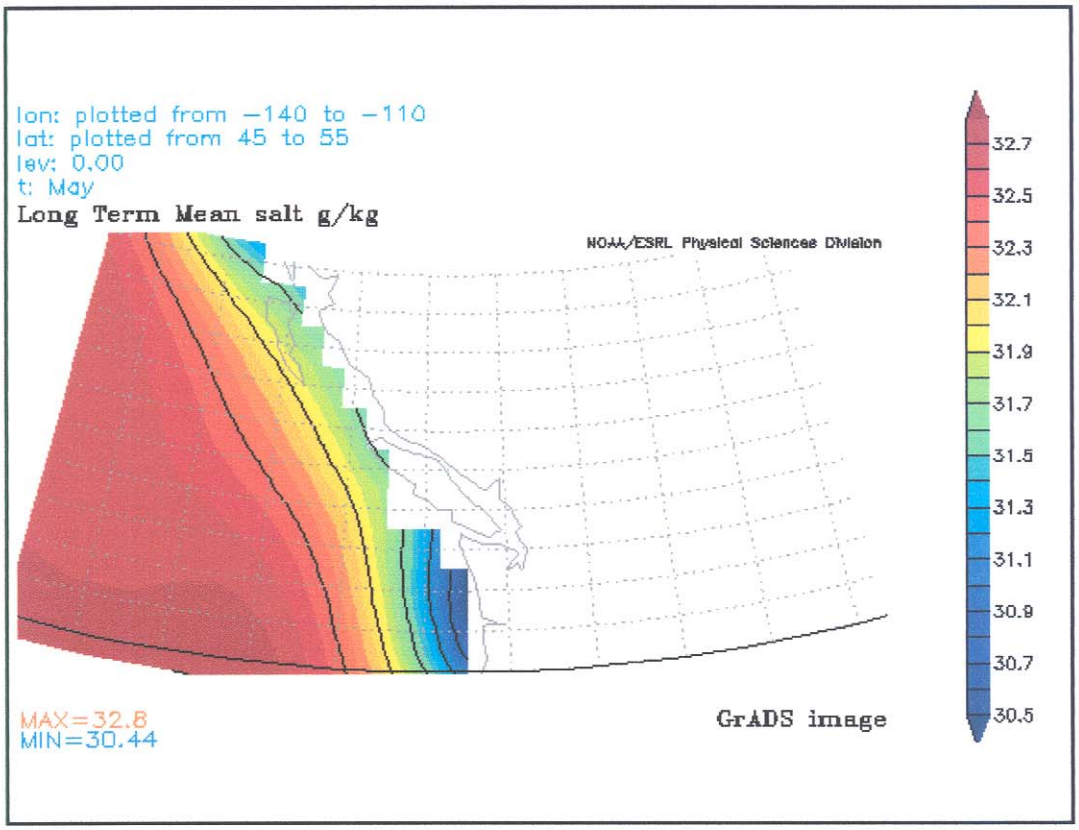
Monthly Isosalinity Maps: Washington
(Levitus) World Ocean Atlas, 1994

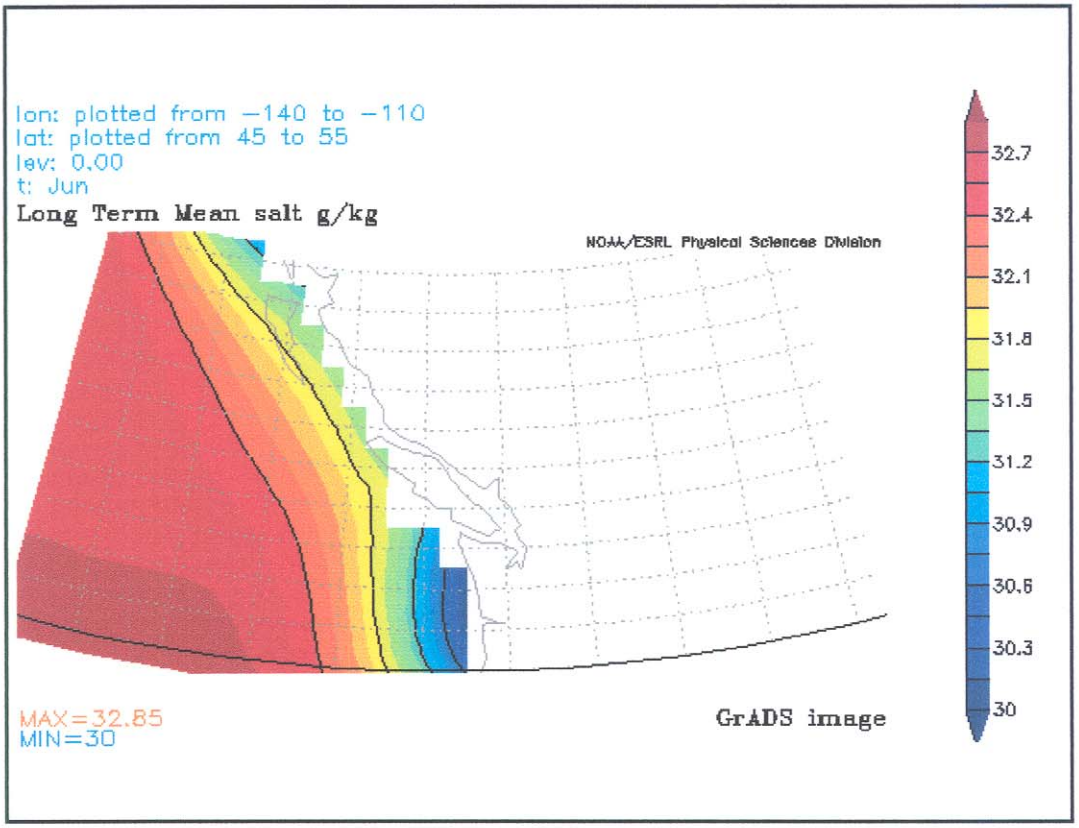

lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Jan
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.8
MAX=32.88
MIN=31.02
GrADS image
32.7
32.5
32.3
32.1
31.9
31.7
31.5
31.3
31.1

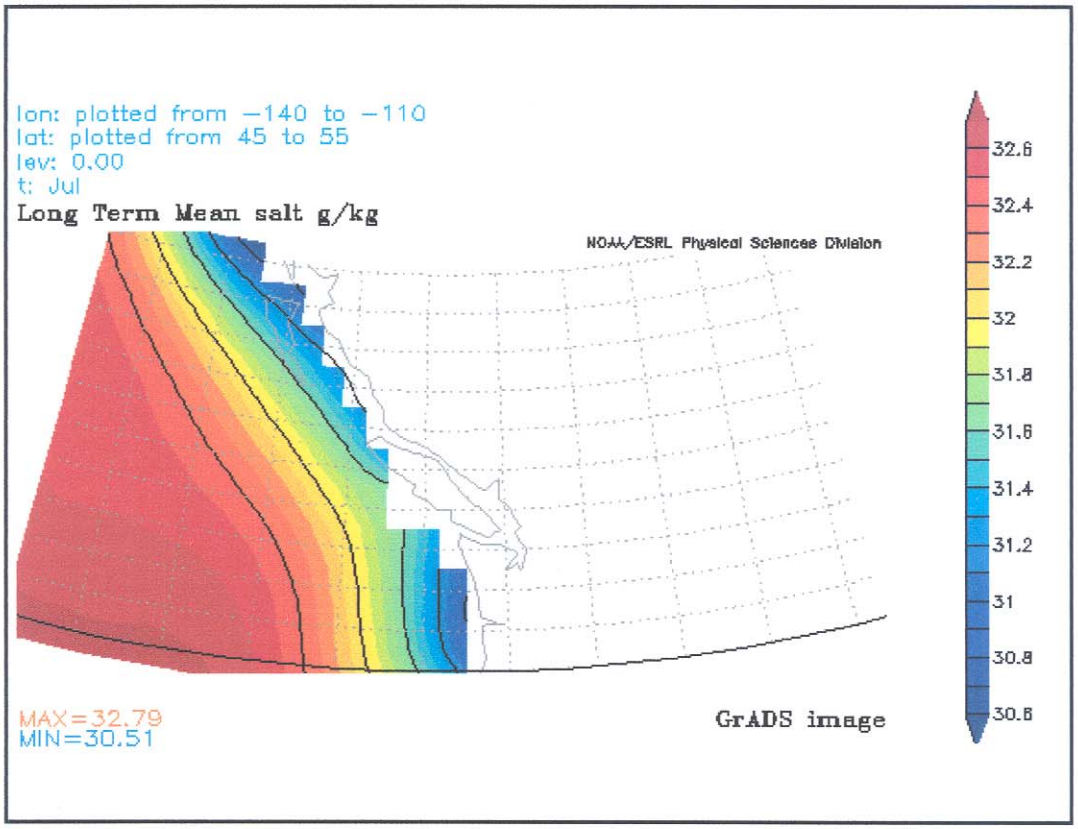

lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Feb
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
MAX=32.89
MIN=30.97
GrADS image
32.8
32.6
32.4
32.2
32
31.8
31.6
31.4
31.2
31

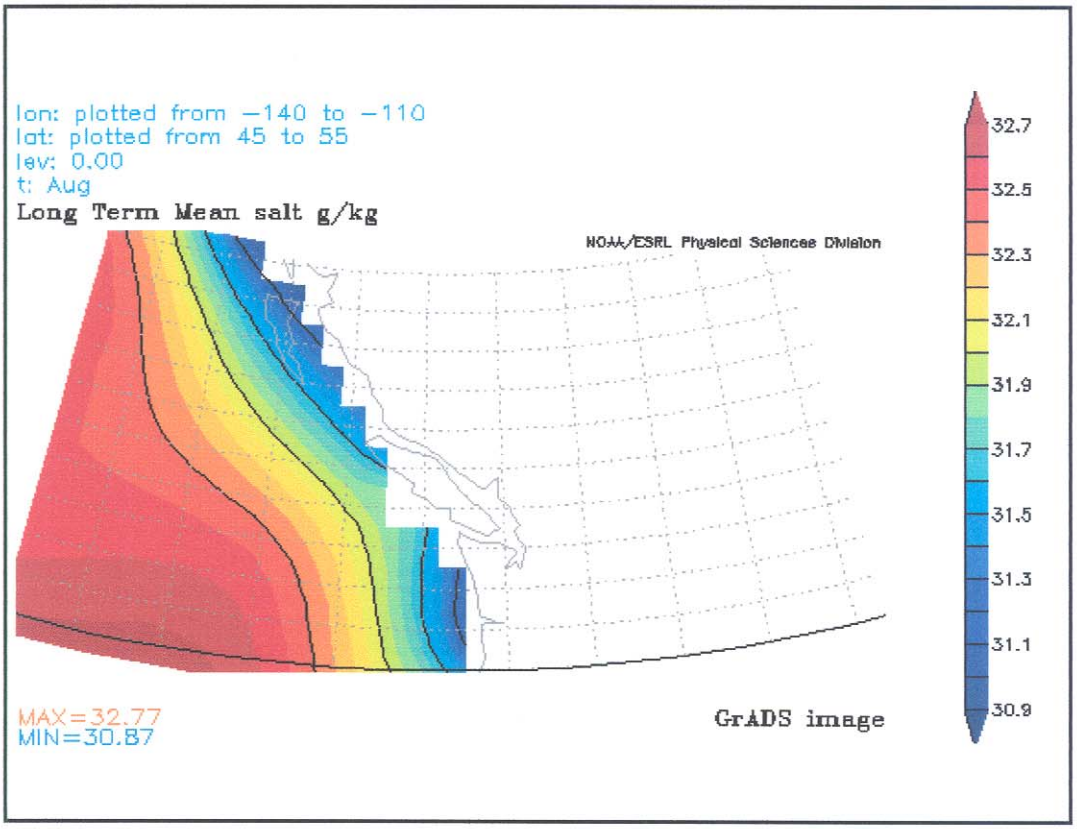

lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Mar
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.7
32.5
32.3
32.1
31.9
31.7
31.5
31.3
31.1
MAX=32.82
MIN=31.02
GrADS image

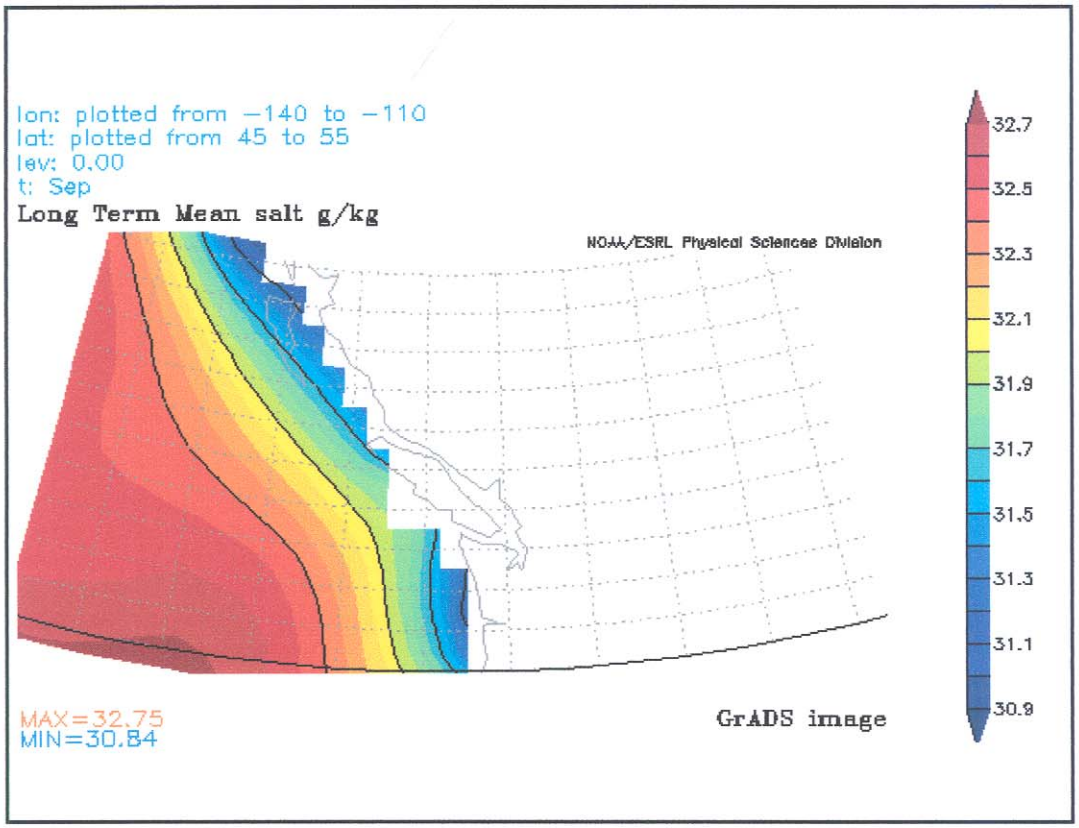

lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Apr
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.8
32.7
32.5
32.3
32.1
31.9
31.7
31.5
31.3
31.1
30.9
30.7
MAX=32.84
MIN=30.69
GrADS image

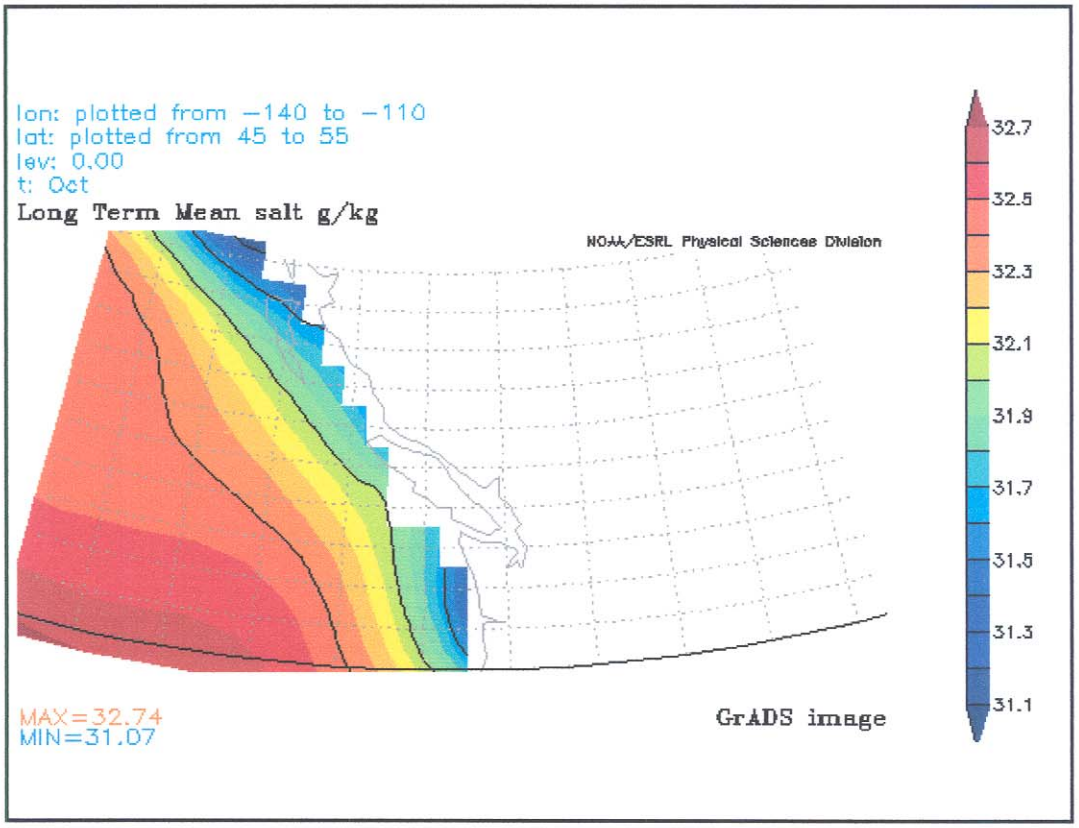

lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: May
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.7
32.5
32.3
32.1
31.9
31.7
31.5
31.3
31.1
30.9
30.7
30.5
MAX=32.8
MIN=30.44
GrADS image

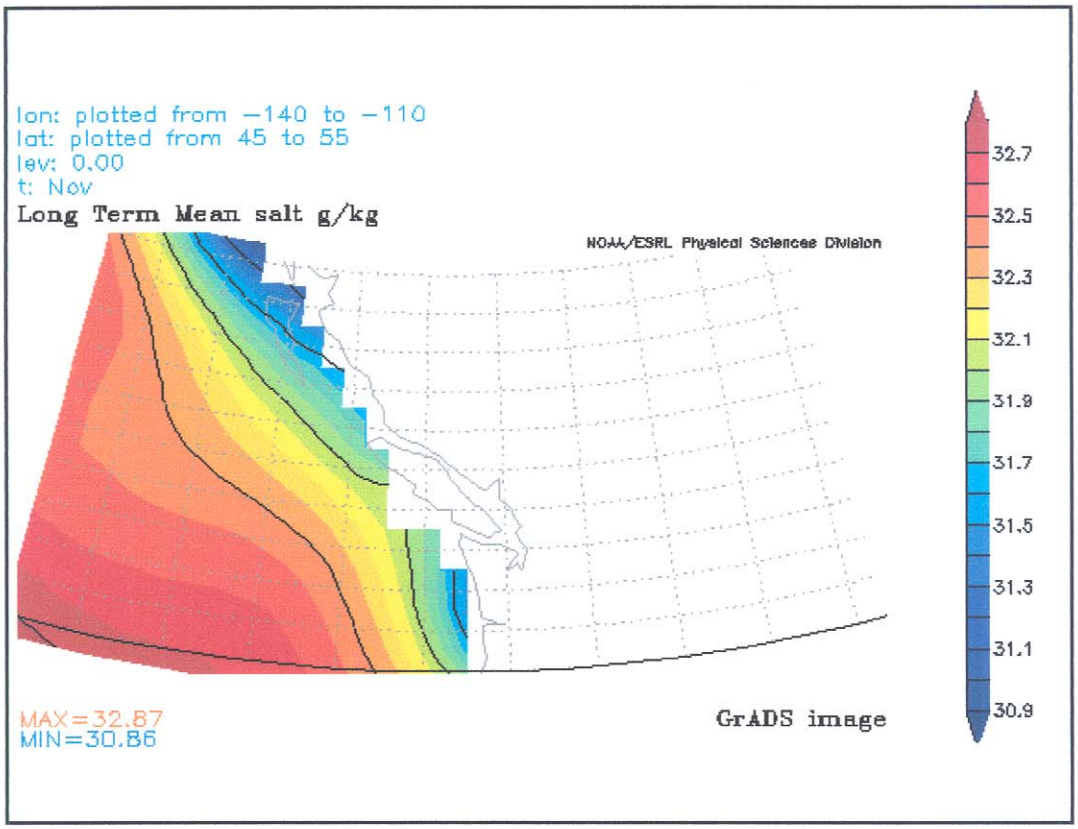

lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Jun
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.7
32.4
32.1
31.8
31.5
31.2
30.9
30.6
30.3
30
MAX=32.85
MIN=30
GrADS image

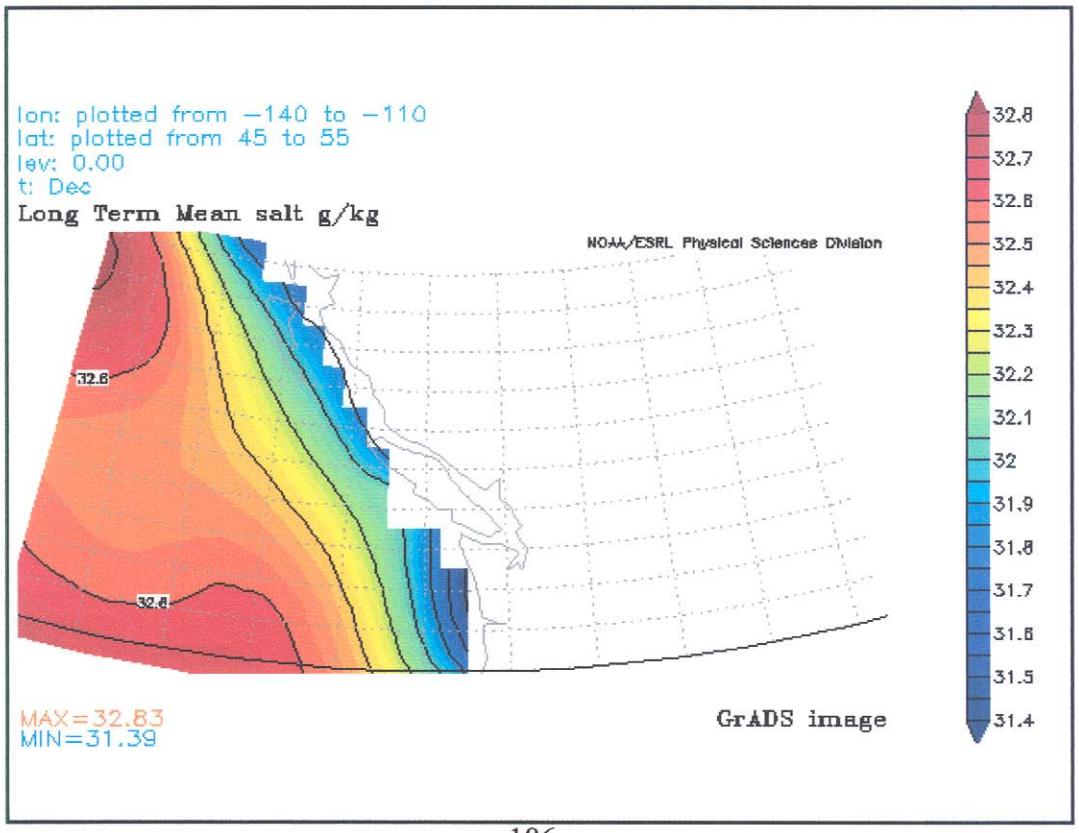

lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Jul
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.6
32.4
32.2
32
31.8
31.6
31.4
31.2
31
30.8
30.6
MAX=32.79
MIN=30.51
GrADS image


lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Aug
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.7
32.5
32.3
32.1
31.9
31.7
31.5
31.3
31.1
30.9
MAX=32.77
MIN=30.87
GrADS image


lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Sep
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.7
32.5
32.3
32.1
31.9
31.7
31.5
31.3
31.1
30.9
MAX=32.75
MIN=30.84
GrADS image


lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Oct
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.7
32.5
32.3
32.1
31.9
31.7
31.5
31.3
31.1
MAX=32.74
MIN=31.07
GrADS image


lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Nov
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.7
32.5
32.3
32.1
31.9
31.7
31.5
31.3
31.1
30.9
MAX=32.87
MIN=30.86
GrADS image


lon: plotted from −140 to −110
lat: plotted from 45 to 55
lev: 0.00
t: Dec
Long Term Mean salt g/kg
NOAA/ESRL Physical Sciences Division
32.8
32.7
32.6
32.5
32.4
32.3
32.2
32.1
32
31.9
31.8
31.7
31.6
31.5
31.4
32.6
32.4
MAX=32.83
MIN=31.39
GrADS image

APPENDIX 4

Seawater δ18O Composition Tables
from the
NASA GISS Global Seawater Oxygen-18 Database

NASA GISS Global Seawater $\delta^{18}O$ Database							
Longitude	Latitude	Depth (m)	pTemperature	Salinity	$\delta^{18}O$	Year	Month
-156.68	71.48	1	2.70	27.10	-1.66	1977	7
-155.13	71.78	0	0.27	27.26	-1.20	1992	8
-155.13	71.78	0	3.50	27.90	-1.10	1992	8
-156.69	71.55	0	2.06	27.73	-0.90	1992	8
-158.34	70.88	0	5.72	29.19	-1.82	1992	8
-158.65	71.22	0	4.27	28.71	-1.10	1992	8
-157.48	71.40	10	-1.06	27.77	-1.59	1993	8
-155.13	71.78	100	-1.61	32.58	-1.04	1992	8
-157.02	71.50	100	-1.71	32.63	-1.15	1993	8
-158.09	71.30	100	-1.58	32.50	-1.35	1993	8
-157.48	71.40	103	-1.66	32.53	-1.29	1993	8
-157.48	71.40	107	-1.70	32.59	-1.16	1993	8
-155.13	71.78	110	-1.70	32.57	-2.01	1992	8
-156.69	71.55	110	-1.36	32.59	-1.14	1992	8
-158.17	71.33	114	-1.34	32.58	-0.93	1992	8
-155.80	71.67	119	-1.73	32.78	-1.33	1992	8
-155.13	71.78	125	-1.71	32.67	-1.24	1992	8
-156.70	71.56	134	-0.41	34.33	-0.66	1992	8
-157.02	71.50	136	-1.71	32.63	-1.10	1993	8
-155.13	71.78	140	-1.72	32.80	-2.10	1992	8
-155.13	71.78	140	-1.19	33.61	-0.99	1992	8
-156.46	71.58	144	-1.61	32.63	-1.30	1992	8
-156.71	71.53	145	-1.42	32.60	-1.22	1992	8
-157.02	71.50	15	-1.11	27.66	-1.37	1993	8
-157.12	72.87	1584	-0.36	34.91	0.46	1993	8
-158.65	71.22	17	4.14	29.05	-0.97	1992	8
-155.13	71.78	170	-1.36	33.44	-1.85	1992	8
-155.13	71.78	175	-0.63	34.47	-0.39	1992	8
-157.02	71.50	2	-1.07	27.64	-1.60	1993	8
-157.48	71.40	2	-1.02	27.71	-1.56	1993	8
-158.09	71.30	2	-0.95	27.43	-1.28	1993	8
-155.13	71.78	200	-0.23	34.59	-0.41	1992	8
-155.13	71.78	225	0.14	34.75	-0.01	1992	8
-155.69	71.65	228	0.11	34.75	-0.03	1992	8
-155.13	71.78	230	0.06	34.73	-0.54	1992	8
-155.13	71.78	25	-1.55	31.38	-1.53	1992	8
-156.69	71.55	25	-1.25	31.93	-1.05	1992	8
-155.13	71.78	260	0.27	34.82	-0.70	1992	8

-155.13	71.78	275	0.39	34.84	-0.06	1992	8
-158.99	72.90	275	0.27	34.72	0.36	1993	8
-155.13	71.78	290	0.32	34.84	-0.68	1992	8
-158.60	71.20	3	-0.50	27.49	-1.21	1993	8
-157.02	71.50	30	-1.27	30.26	-1.19	1993	8
-155.13	71.78	310	0.37	34.85	0.19	1992	8
-155.13	71.78	315	0.33	34.85	-0.66	1992	8
-157.46	72.77	333	0.45	34.77	0.46	1993	8
-158.65	71.22	37	-1.36	32.42	-1.02	1992	8
-155.13	71.78	40	0.05	32.31	-0.99	1992	8
-158.60	72.25	46	-1.69	32.67	-0.97	1993	8
-157.02	71.50	5	-1.05	27.64	-1.47	1993	8
-155.13	71.78	50	-1.61	32.35	-1.68	1992	8
-156.69	71.55	50	-0.69	32.40	-1.14	1992	8
-157.02	71.50	50	-1.72	32.57	-1.22	1993	8
-158.65	71.22	57	-1.20	32.49	-1.11	1992	8
-157.02	71.50	75	-1.71	32.63	-1.25	1993	8
-158.60	71.20	75	-1.55	32.46	-1.31	1993	8
-158.65	71.22	77	-1.24	32.51	-1.62	1992	8
-157.43	72.78	785	0.22	34.86	-1.60	1993	8
-156.25	71.41	8	4.94	28.84	-1.99	1992	8
-158.34	70.87	8	4.94	28.84	-1.90	1992	8
-155.13	71.78	80	-1.70	32.51	-1.30	1992	8
-155.13	71.78	80	-1.28	32.50	-1.13	1992	8
-156.69	71.55	90	-1.33	32.58	-1.12	1992	8
-158.65	71.22	97	-1.27	32.52	-1.37	1992	8
-157.22	71.44	129	0.28	34.78	0.65	1993	9
-155.21	71.73	3	4.54	30.43	-1.91	1993	9
-155.21	71.73	302	0.26	34.83	0.28	1993	9
-158.82	70.98	10	0.35	30.26	-0.92	1992	10
-158.88	71.01	10	0.51	30.32	-1.10	1992	10
-158.97	71.04	10	1.38	30.72	-0.85	1992	10
-155.88	71.67	101	-1.23	33.14	-1.08	1984	10
-155.88	71.67	114	-1.15	33.40	-1.02	1984	10
-155.88	71.67	20	2.83	31.77	-0.90	1984	10
-158.82	70.98	24	0.36	30.26	-1.00	1992	10
-158.88	71.01	30	0.54	30.34	-0.79	1992	10
-158.97	71.04	45	3.15	31.62	-0.79	1992	10
-155.88	71.67	51	3.50	32.07	-0.94	1984	10
Astarte compacta Carpenter, 1864; IZ&G 173948; Alaska, Arctic Ocean, 17 mi W of Arcon Beach: 71.00°21.00' 30.00"N 157.00°23.00' 0.00" W, Depth 300 ft, Coll G.D. Hanna 19 Aug, 1954; *Macoma calcarea* (Gmelin, 1791); Alaska, Point Barrow, Deadman Island							

NASA GISS Global Seawater $\delta^{18}O$ Database							
Longitude	Latitude	Depth (m)	pTemperature	Salinity	$\delta^{18}O$	Year	Month
-161.90	70.33	1	7.00	30.50	-1.64	1977	7
-159.28	72.80	36	-1.61	32.02	-1.16	1993	8
-159.28	72.80	170	-0.18	34.52	0.00	1993	8
-159.29	71.10	2	0.82	27.91	-1.10	1993	8
-159.29	71.10	78	-1.54	32.49	-1.33	1993	8
-159.40	71.11	75	-0.76	32.52	-1.34	1992	8
-159.42	72.75	95	-1.71	32.76	-0.98	1993	8
-159.50	72.70	75	-1.73	32.75	-1.04	1993	8
-159.56	71.01	5	1.46	29.26	-1.16	1993	8
-159.56	71.01	65	1.38	31.38	-1.64	1993	8
-159.68	72.65	60	-1.73	32.80	-1.08	1993	8
-159.80	72.50	35	-1.73	32.80	-1.20	1993	8
-159.84	71.05	49	-0.63	32.51	-1.01	1992	8
-160.18	70.90	2	1.74	29.25	-1.20	1993	8
-160.18	70.90	50	1.70	31.66	-1.53	1993	8
-160.58	72.82	45	-1.42	32.59	-0.93	1993	8
-162.85	70.43	24	5.34	31.34	-1.85	1992	8
-164.25	71.28	38	-1.29	32.44	-1.11	1993	8
-164.65	70.31	0	7.05	31.03	-1.78	1992	8
-164.65	70.31	35	3.77	32.22	-1.30	1992	8
-159.28	70.98	6	5.43	30.54	-1.42	1993	9
-159.28	70.98	48	5.47	30.57	-2.11	1993	9
-159.53	71.06	6	5.32	30.58	-2.01	1993	9
-159.53	71.06	79	2.11	31.71	-1.61	1993	9
-159.56	70.94	54	-1.58	33.35	-1.17	1990	9
-159.66	71.06	71	1.23	31.87	-1.09	1990	9
-159.81	71.08	53	-1.68	33.39	-1.03	1990	9
-159.90	71.16	8	5.45	30.56	-1.47	1993	9
-159.90	71.16	65	4.74	31.21	-1.34	1993	9
-159.95	71.15	62	-1.70	33.38	-1.00	1990	9
-160.22	71.30	44	-1.01	32.90	-1.10	1990	9
-160.91	71.52	44	4.10	31.66	-0.76	1993	9
-161.25	71.88	35	-1.12	33.02	-0.96	1990	9
-161.58	71.75	9	1.32	29.32	-1.41	1993	9
-161.58	71.75	24	0.51	31.93	-0.96	1993	9
-161.81	72.16	30	-0.98	33.06	-0.91	1990	9
-162.39	72.45	36	-0.94	32.89	-0.87	1990	9
-162.50	71.58	41	1.62	32.04	-1.17	1993	9
-162.96	72.92	55	-1.11	32.99	-0.77	1990	9
-163.76	70.13	25	7.21	30.24	-2.29	1990	9

-164.19	71.30	43	0.37	32.22	-1.01	1993	9
-159.06	71.06	11	-0.42	30.21	-0.83	1992	10
-159.06	71.06	60	2.85	32.23	-0.91	1992	10
-159.16	71.08	10	-0.12	30.25	-1.15	1992	10
-159.16	71.08	75	0.47	32.36	-0.84	1992	10
-159.24	70.95	4	0.28	30.30	-0.69	1992	10
-159.24	70.95	28	1.32	30.74	-1.23	1992	10
-159.25	71.09	10	-1.58	30.01	-0.22	1992	10
-159.25	71.09	80	-0.39	32.55	-0.69	1992	10
-159.57	70.95	5	0.23	30.44	-0.75	1992	10
-159.57	70.95	50	3.28	32.27	-0.90	1992	10
-159.57	71.02	72	-0.12	32.54	-0.96	1992	10
-160.00	70.83	7	0.44	30.40	-0.62	1992	10
-160.00	70.83	41	3.50	32.18	-0.88	1992	10
-160.51	70.83	5	0.23	30.77	0.13	1992	10
-160.51	70.83	48	2.13	32.33	-0.60	1992	10
-161.02	70.82	7	0.07	30.73	-0.03	1992	10
-161.02	70.82	42	1.84	32.34	-1.28	1992	10
-161.52	70.82	10	0.27	30.66	-0.73	1992	10
-161.52	70.82	41	2.83	32.36	-1.74	1992	10
-162.04	70.82	10	0.07	30.68	-0.69	1992	10
-162.04	70.82	40	2.80	32.38	-0.66	1992	10
-162.55	70.82	7	0.10	30.70	-0.27	1992	10
-162.55	70.82	41	2.82	32.40	-0.92	1992	10
-163.84	70.83	6	0.45	30.98	-0.82	1992	10
-163.84	70.83	41	1.05	32.36	-0.90	1992	10
-164.86	70.84	10	-0.57	30.50	-0.18	1992	10
-164.86	70.84	34	1.12	32.33	-0.75	1992	10
Cyrtodaria kurriana Dunker, 1862; Chukchi Sea, 70.00'50.00"N, 162.00'9.00"W, 32 m, USGC Glacier 10 Aug 1976							

NASA GISS Global Seawater $\delta^{18}O$ Database							
Longitude	Latitude	Depth (m)	pTemperature	Salinity	$\delta^{18}O$	Year	Month
-20.03	69.01	27	1.96	33.65	-0.35	1972	8
-22.98	66.73	20	7.62	35.03	0.25	1998	10
-22.98	66.73	30	7.65	35.03	0.26	1998	10
-22.98	66.73	47	7.56	35.04	0.23	1998	10
-22.98	66.73	75	7.44	35.04	0.25	1998	10
-22.98	66.73	98	7.41	35.04	0.25	1998	10
-23.05	67.00	18	-0.54	33.28	-1.21	1998	10
-23.05	67.00	49	-0.82	33.69	-0.82	1998	10
-23.05	67.00	100	5.61	34.96	0.23	1998	10
-23.05	67.00	200	0.85	34.54	-0.07	1998	10
-23.05	67.00	252	1.20	34.69	0.09	1998	10
-23.15	67.33	10	3.76	34.22	-0.46	1998	10
-23.15	67.33	19	4.64	34.49	-0.11	1998	10
-23.15	67.33	29	4.58	34.48	-0.07	1998	10
-23.15	67.33	49	4.63	34.49	-0.14	1998	10
-23.15	67.33	75	5.29	34.62	-0.06	1998	10
-23.15	67.33	100	4.91	34.67	-0.02	1998	10
-23.15	67.33	200	1.88	34.72	0.07	1998	10
-23.15	67.33	300	0.41	34.81	0.14	1998	10
-23.15	67.33	349	-0.26	34.87	0.28	1998	10
-23.15	67.33	395	-0.44	34.88	0.21	1998	10
-23.25	67.67	20	2.81	34.19	-0.13	1998	10
-23.25	67.67	30	3.72	34.34	-0.11	1998	10
-23.25	67.67	49	3.76	34.35	-0.16	1998	10
-23.25	67.67	98	-1.41	34.30	-0.19	1998	10
-23.25	67.67	199	0.46	34.70	0.14	1998	10
-23.25	67.67	297	0.34	34.82	0.23	1998	10
-23.25	67.67	500	-0.01	34.88	0.29	1998	10
-23.25	67.67	701	-0.44	34.89	0.25	1998	10
-23.25	67.67	798	-0.53	34.90	0.28	1998	10
-23.38	68.17	10	-0.19	32.09	-1.39	1998	10
-23.38	68.17	50	1.05	34.10	-0.26	1998	10
-23.38	68.17	76	1.65	34.30	-0.04	1998	10
-23.38	68.17	100	-1.20	34.26	-0.26	1998	10
-23.38	68.17	301	1.41	34.92	0.22	1998	10
-23.38	68.17	500	0.45	34.90	0.25	1998	10
-23.38	68.17	699	-0.11	34.89	0.22	1998	10
-23.38	68.17	900	-0.41	34.89	0.18	1998	10
-23.38	68.17	1100	-0.53	34.90	0.21	1998	10
-23.38	68.17	1299	-0.65	34.91	0.21	1998	10
-23.47	68.50	9	-0.70	32.44	-1.61	1998	10

-23.47	68.50	50	-1.47	33.59	-0.89	1998	10
-23.47	68.50	100	0.76	34.21	-0.31	1998	10
-23.47	68.50	300	1.07	34.89	0.23	1998	10
-23.47	68.50	501	0.51	34.89	0.27	1998	10
-23.47	68.50	700	0.12	34.89	0.19	1998	10
-23.47	68.50	800	0.06	34.89	0.23	1998	10
-23.47	68.50	900	-0.14	34.89	0.26	1998	10
-23.47	68.50	1199	-0.44	34.89	0.27	1998	10
-23.47	68.50	1480	-0.61	34.91	0.25	1998	10
-23.55	68.72	20	0.22	32.40	-1.69	1998	10
-23.55	68.72	49	-1.52	33.22	-1.54	1998	10
-23.55	68.72	73	-1.45	33.58	-1.21	1998	10
-23.55	68.72	99	-0.86	33.88	-0.70	1998	10
-23.55	68.72	150	-1.35	34.24	-0.33	1998	10
-23.55	68.72	199	-0.19	34.51	-0.02	1998	10
-23.55	68.72	400	0.57	34.85	0.19	1998	10
-23.55	68.72	489	0.53	34.88	0.17	1998	10
-23.55	68.72	588	0.34	34.89	0.15	1998	10
-23.65	69.03	9	-1.28	29.17	-2.26	1998	10
-23.65	69.03	20	-0.43	30.64	-1.83	1998	10
-23.65	69.03	50	-0.26	32.06	-1.72	1998	10
-23.65	69.03	74	-1.24	32.81	-1.08	1998	10
-23.65	69.03	101	-1.51	33.33	-1.14	1998	10
-23.65	69.03	200	-0.85	34.41	-0.14	1998	10
-20.04	69.02	27	1.97	33.66	-0.36	1972	8
-22.98	66.73	20	7.62	35.03	0.25	1998	10
-22.98	66.73	30	7.65	35.03	0.26	1998	10
-22.98	66.73	47	7.56	35.04	0.23	1998	10
-22.98	66.73	75	7.44	35.04	0.25	1998	10
-22.98	66.73	98	7.41	35.04	0.25	1998	10
-23.05	67.00	18	-0.110	33.110	-1.22	1998	10
-23.05	67.00	49	-0.138	33.151	-0.83	1998	10
-23.05	67.00	100	5.62	34.96	0.24	1998	10
-23.05	67.00	200	0.86	34.54	-0.08	1998	10
-23.05	67.00	252	1.21	34.69	0.10	1998	10
-23.15	67.33	10	3.77	34.22	-0.46	1998	10
-23.15	67.33	19	4.64	34.49	-0.11	1998	10
-23.15	67.33	29	4.58	34.48	-0.07	1998	10
-23.15	67.33	49	4.63	34.49	-0.14	1998	10
-23.15	67.33	75	5.30	34.62	-0.06	1998	10
-23.15	67.33	100	4.92	34.67	-0.02	1998	10
-23.15	67.33	200	1.89	34.72	0.07	1998	10
-23.15	67.33	300	0.42	34.81	0.14	1998	10
Arctica islandica (Linnaeus 1767) Iceland, Gufunes, Coll: 22 Jun 1974, Depth 10 m							