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A CLIMATOLOGICAL ANALYSIS OF EASTERN CANADIAN SEABOARD MAXIMUM
ICE EXTENT USING PASSIVE MICROWAVE SATELLITE DATA (1973-1985)

by

ANNE E. WALKER, B.A.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Arts

Department of Geography

Carleton University

Ottawa, Ontario

July 31, 1986

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A CLIMATOLOGICAL ANALYSIS OF EASTERN CANADIAN SEABOARD MAXIMUM ICE
EXTENT USING PASSIVE MICROWAVE SATELLITE DATA (1973-1985)

submitted by Anne Elizabeth Walker

B.A. Carleton University

in partial fulfilment of the requirements for
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ABSTRACT

Values for Eastern Canadian Seaboard maximum sea ice area and extent are derived from Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR) and Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) satellite passive microwave data. Interannual variation in maximum ice extent is investigated covering the 13 years (1973-1985) of archived data, through comparisons to several climatological and oceanographic variables. The objective is to account for the variation seen in the maximum ice values, and attempt to isolate any controlling parameters. Trends in seasonal (winter) air temperature means, freezing degree day accumulations and sea surface temperature anomalies exhibit the highest correlations with the maximum ice extent and area trends. Comparison with Icelandic Low winter positions does not yield a significant correlation, suggesting that the role of atmosphere-ocean interaction in determining maximum ice extent bears further research.

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TABLE OF CONTENTS

	Page
ACCEPTANCE SHEET	ii
ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF TABLES	viii
LIST OF FIGURES	viii
CHAPTER 1: Introduction	
1.1 General Background	1
1.2 Goals and Objectives	3
1.3 Thesis Organization	4
CHAPTER 2: Theoretical Background	
2.1 Development of Satellite Passive Microwave Remote Sensing	6
2.1.1 Nimbus-5 and ESMR	6
2.1.2 Nimbus-6 and ESMR	8
2.1.3 Nimbus-7 and SMMR	10
2.2 Passive Microwave Remote Sensing	11
2.2.1 Microwave Emissivity	11
2.2.2 Brightness Temperature	16
2.3 Sea Ice and Climate	19
2.3.1 Sea Ice and Atmospheric Interactions	19
2.3.2 Sea Ice Parameters of Climatic Interest	21
2.3.3 Role of Passive Microwave Data	22
CHAPTER 3: Characteristics of the Eastern Canadian Seaboard	
3.1 Definition of the Study Area	24
3.2 Climate	24
3.2.1 Air Temperature	24
3.2.2 Air Pressure	27
3.2.3 Winds	29
3.3 Oceanography	29
3.3.1 Currents	31
3.3.2 Sea Surface Temperature	33
3.4 Sea Ice Regime	33
3.4.1 Ice Characteristics	35
3.4.2 Factors Determining Ice Extent	36

CHAPTER 4: Analysis of Interannual Sea Ice Variation	
4.1 Format of the Passive Microwave Data	39
4.2 Sea Ice Algorithms	40
4.2.1 Simple Linear Algorithm	40
4.2.2 AES/Ph.D. Algorithm	44
4.3 Display of the Ice Concentration Data	46
4.4 Analysis Methodology for Interannual Variation	47
4.4.1 Dates of Maximum Ice Extent	47
4.4.2 Quantitative Analysis	51
4.4.2.1 Methodology of Statistics Derivation	51
4.4.2.2 Computer and Manual Statistics Derivation	52
4.4.2.3 Trends in Ice Area and Extent	54
4.5 Validation of Ice Area and Extent Trends	54
CHAPTER 5: Explanation of Sea Ice Interannual Variation	
5.1 Introduction	61
5.2 Climatological Parameters	62
5.2.1 Air Temperature	62
5.2.2 Accumulated Freezing Degree Days	67
5.2.3 Position of the Icelandic Low	69
5.2.4 Winds	76
5.3 Oceanographic Parameters	78
5.3.1 Sea Surface Temperature	78
5.4 Significance of the Climatological and Oceanographic Comparisons	85
5.5 Regional Maximum Ice Extent Analysis	88
5.6 Climatic Significance of Maximum Ice Extent Trends	92
CHAPTER 6: Concluding Remarks	
6.1 Summary of the Interannual Variability Analysis	95
6.2 Limitations of Methods and Data	96
6.3 Implications for the Canadian Offshore Scenario	97
6.4 Applications to Climate Research	98
6.5 The Future of Passive Microwave Satellite Remote Sensing	99
APPENDIX A.1: Maps Displaying Maximum Ice Extent Conditions (1973-1985)	101
APPENDIX A.2: Ice Area and Extent Statistics (1973-1985)	114
APPENDIX A.3: Air Temperature and FFD Data for Meteorological Stations Along the Eastern Canadian Seaboard	117
APPENDIX A.4: Accessibility of Nimbus-5 ESMR and Nimbus-7 SMMR Data	122
BIBLIOGRAPHY	123

LIST OF TABLES

TABLE	DESCRIPTION	PAGE
2.1	History of Satellite Passive Microwave Remote Sensing ..	7
2.2	ESMR and SMMR Performance Characteristics	9
4.1	Maximum Ice Extent and Area Values (1973-1985)	56
5.1	Eastern Canadian Seaboard February and March Mean Air Temperatures (°C) (1973-1985)	63
5.2	Eastern Canadian Seaboard Seasonal Air Temperature Means (December to February, 1973-1985)	66
5.3	Freezing Degree Day Accumulations for the Eastern Canadian Seaboard to the End of February (1973-1985) ...	70
5.4	Classifications of Icelandic Low Positions and Eastern Canadian Seaboard Maximum Ice Extents (1973-1985)	74
5.5	February Prevailing Wind Directions and Speeds (km/hr) (1973-1985)	77
5.6	Sea Surface Temperature Anomalies (°C) for the Eastern Canadian Seaboard (1973-1982)	82
5.7	Maximum Ice Extent and Area Values for the Eastern Canadian Seaboard Regions (1979-1985)	91
6.1	SSM/I Performance Characteristics	100

LIST OF FIGURES

FIGURE	DESCRIPTION	PAGE
2.1	Emissivity vs Frequency Relationship for Sea Ice Types and Open Water	13
2.2a	The Physical Properties of First Year Ice	14
2.2b	The Physical Properties of Old Ice	14
2.3	The Radiative Transfer Equation	18
2.4	The Atmosphere-Ocean Energy Balance System	20
3.1	The Eastern Canadian Seaboard and Subregions	25
3.2	Eastern Canadian Seaboard Air Temperature Statistics ...	26
3.3	Typical Winter Surface Pressure Distribution for Eastern Canada	28
3.4	Typical Winter East Coast Wind Velocities	30
3.5	Major Ocean Currents Along the Eastern Canadian Seaboard	32
3.6	Typical Winter Sea Surface Temperatures Along the Eastern Canadian Seaboard	34
4.1	The Simple Linear Algorithm	41
4.2	The Increase in T_B at 19.35 GHz Caused by Wind Speed Over an Ocean Surface	43
4.3	The AES/Ph.D. Algorithm	45
4.4	Example of Map Portraying Passive Microwave Derived Ice Concentrations	48
4.5	Extremes in Maximum Ice Extent Position (1973-1985)	50
4.6	Eastern Canadian Seaboard Maximum Ice Area and Extent (1973-1985)	55
4.7	Example of Eastern Canadian Seaboard Portion of a British Meteorological Office Ice Chart (February 1984)	58

4.8	Maximum Ice Extents and Areas from British Meteorological Office (BMO) Ice Charts as Compared to Passive Microwave Trends (1974-1984)	59
5.1	Trends in Ice Area and Extent Compared to February and March Mean Air Temperatures (1973-1985)	64
5.2	Trends in Ice Area and Extent Compared to Seasonal (Winter) Air Temperatures (1973-1985)	68
5.3	Trends in Ice Area and Extent Compared to Eastern Canadian Seaboard FDD Accumulations (1973-1985)	71
5.4	Mean January-February Position of the Icelandic Low (1973-1985)	73
5.5	The NAFO Convention Area	80
5.6	Trends in Ice Area and Extent Compared to East Coast Sea Surface Temperature Anomalies (1973-1982)	83
5.7	Annual Sea Surface Temperature Anomalies for the Eastern Canadian Seaboard (1972-1983)	84
5.8	Eastern Canadian Seaboard Regional Trends in Maximum Ice Extent and Ice Area (1979-1985)	89
5.9	Median Maximum Ice Extents from AES Ice Charts (1963-1973) and Passive Microwave Data (1973-1985)	94

CHAPTER 1

INTRODUCTION

1.1 General Background

Over the past several years, the East Coast region has become the focus for offshore oil and gas development. The presence of sea ice along the Eastern Canadian Seaboard during the winter months presents a barrier and hazard to offshore operations. The variability in ice conditions and extent from year to year makes it difficult to predict to what extent operations will be affected during the season. If the forecast of even greater activity in the Eastern offshore becomes reality, it will be necessary to obtain a greater understanding of ice limits and variability in this region. The need of a greater understanding of East Coast maximum ice extent has been emphasized recently by Wadhams and Lever (1985) in their preliminary science plan for the Labrador Ice Margin Experiment (LIMEX), due to take place in 1987. They indicate that this type of research will lead to more efficient marine operations in the Eastern Canadian offshore waters.

Satellite remote sensing provides one of the best sources of information for sea ice reconnaissance, by allowing one to view large areas of the earth's surface instantaneously. Surveillance of remote regions, inaccessible by traditional reconnaissance methods, is therefore possible on a daily basis. Passive microwave methods have the

advantages of day and night sensing capability, and the ability to penetrate clouds, haze and most forms of precipitation. These advantages make passive microwave sensing very effective for sea ice studies, since many ice-covered regions are in total darkness for part of the year. The East Coast region is subject to stormy, unsettled weather during the winter months, in some cases to the degree as to inhibit visual ice reconnaissance. In fact, in the winter months the region may be totally obscured by cloud or fog over 50% of the time (Gustajtis, 1979). Passive microwave sensors are therefore particularly suited to monitoring sea ice in this area, by providing the all-weather capability to supplement traditional aerial reconnaissance (Mullane, 1980).

The launch of the Electrically Scanning Microwave Radiometer (ESMR) on board NASA's Nimbus-5 satellite in 1972 signalled the beginning of continuous monitoring of the earth's surface using a passive microwave sensor. The launch of the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) in 1978 ensured the continuation of passive microwave satellite sensing. The SMMR is still in operation today. Therefore the data set that has been accumulated from the two sensors spans over 13 years (1972-1986). The archived data, stored on computer tape, can be a useful data base for studies of regional or hemispheric ice conditions, especially studies of interannual variability.

Sea ice plays an important role in the global climate system. The areal extent of ice covering the oceans affects the global heat budget, as it prevents heat from escaping from the oceans to the atmosphere. The interannual variability of sea ice extent can be an important

indicator of climatic change. By providing reliable and consistent ice extent information, passive microwave data sets can therefore make an important contribution to studies of the sea ice/climate relationship, as illustrated by Zwally et al. (1983), Crane (1983) and Carleton (1984), to name a few.

1.2" Goals and Objectives

The availability of such an extensive and complete data set of satellite ice information lends itself especially to the analysis of variability in ice conditions on the Eastern Canadian Seaboard. This region has frequently been ignored in terms of sea ice studies, with greater interest in more polar regions of the Arctic and Antarctic. The objective of this thesis is to examine the interannual variability in East Coast maximum ice extent from 1973 to 1985, and compare the trend to several climatological and oceanographic parameters. The aim is to account for the observed interannual variability and attempt to define the main factors controlling maximum ice extent on the Eastern Seaboard.

The climatological parameters to be examined include air temperature, prevailing wind direction, and atmospheric pressure patterns, concentrating on the time period corresponding to maximum ice conditions (February and March). Sea surface temperature will be the main oceanographic parameter of interest in the analysis. By comparing archived data concerning these parameters to the trend in sea ice extent, it is hoped that a greater understanding of ice limits and their variability will be gained. The comparisons will incorporate statistical procedures

(i.e., correlation) and visual (qualitative) examination of the data.

A secondary goal of the thesis is to illustrate the usefulness of sea ice information, derived from satellite passive microwave data, to climate studies. Sea ice plays an important role in the global climate system, and satellites can provide consistent and reliable information about global sea ice limits (European Space Agency, 1985). Sea ice concentrations derived from passive microwave data can be an important input to climate models, leading to a greater understanding of sea ice and climate interactions.

1.3 Thesis Organization

The following chapters lead through consecutive stages of the research by providing background material, details of the analytical procedures and discussion of the subsequent results. Chapter 2 focusses on the history and theoretical basis of satellite passive microwave remote sensing, with respect to sea ice research. The importance of sea ice within the climate scenario is also outlined, emphasizing the role of passive microwave data to sea ice/climate studies. Chapter 3 presents a description of the climatic and oceanographic nature of the Eastern Canadian Seaboard around the time of maximum ice extent. The typical sea ice regime is also described, and factors believed to influence maximum ice extent are outlined. Chapter 4 focusses on the analysis methodology by first discussing the derivation of ice concentrations from the passive microwave data. The generation of maximum sea ice area and extent values for each year, 1973 to 1985, from the ice concentrations is outlined. These values form the basis of the

interannual variability trend in maximum ice extent of the Eastern Canadian Seaboard. Chapter 5 compares the trend in maximum ice extent to the climatological and oceanographic parameters. Chapter 6 summarizes the research presented in the preceding chapters, and outlines the significance of the results to the East Coast scenario. Areas of future research are also suggested in light of the future of satellite passive microwave data.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 Development of Satellite Passive Microwave Remote Sensing

A review of passive microwave remote sensing of the earth from space is given by Njoku (1982). Table 2.1 summarizes the history of microwave radiometry on spacecraft, providing details of the missions involved.

The Soviet COSMOS satellites launched in 1968 and 1970 yielded the first recordings of passive microwave radiation from the earth's surface at a range of frequencies from 3.5 to 37 GHz. Sea ice concentration was one of the parameters investigated during these missions (Njoku, 1982).

The Nimbus series of satellites (5 through 7) launched by NASA has given the most extensive set of observations on record, beginning in 1972 until the present. Details regarding these satellites and the results specific to sea ice research are described in the following subsections.

2.1.1 Nimbus-5 and ESMR

The Nimbus-5 satellite was launched on December 11, 1972 with one of its sensors being the Electrically Scanning Microwave Radiometer (ESMR). The ESMR is a single frequency passive microwave radiometer, operating at the 19.35 GHz frequency in the horizontal polarization, and

TABLE 2.1

History of Satellite Passive Microwave Remote Sensing

Year of Launch	Satellite	Instrument	Frequencies (MHz)	Antenna Type	Swath Width of Scan (km)	Swath Resolution Element (km)	Principal Parameters Measured or Inferred
1966	Mariner 10 (NASA)		15.8, 20.2	Mechanically scanned parabola	Planetary	1300 m	Line defining of planetary emission, temperature
1966	Cosmos 241		13.5, 8.8	Radio-viewing parabola		11	Atmosphere water vapor content, liquid water content, surface sea temperature, sea ice concentration
1970	Cosmos 186		22.2, 33.7				
1972	Nimbus-3	ESR	19.3	Electrically scanned array	3000	25	Atmosphere rain rate, surface sea ice concentration, ice classification
		WERS	22.2, 31.4, 53.6, 54.9, 58.8	Five lens-loaded horns, nadir-viewing		200	Atmosphere temperature profile, water vapor content, liquid vapor content, surface ice classification, snow cover
1973	Skylab	S-193	13.9	Mechanically scanned parabola	800	16	Surface winds, precipitation
		S-196	14	Nadir-viewing array		115	Surface soil moisture
1974	Meteosat		37	Dual polarization 35° from nadir			Atmosphere liquid water content
1975	Nimbus-6	ESR	37	Electrically scanned array, dual-polarization	1300	20 x 43	Same as Nimbus-3 ESR
		SCARS	27.2, 31.6, 52.8, 53.8, 55.4	Three rotating hyperbolic mirrors	2700	150	Same as Nimbus-3 ERS
1978	Block 5U	SSW/7	50.5, 53.2, 54.3, 54.9, 58.4, 58.8, 59.4	Single rotating mirror	1600	175	Atmosphere temperature profile
1978	Terra-M (2 satellites)	MSU	50.3, 53.2, 55.0, 57.9	Dual rotating mirrors	2300	110	Atmosphere temperature profile
1978	Seasat	SMR	6.6, 10.7, 18, 21, 37	Offset-fed oscillating parabola, dual-polarization	800	12 x 28	Atmosphere water vapor content, liquid water content, rain rate
1978	Nimbus-7				800	22 x 35	Surface sea temperature, wind speed, sea ice concentration, ice classification, snow cover, soil moisture

Source: Njoku (1982)

with a ground resolution of 30 km. A list of its performance characteristics appears in Table 2.2.

One of the main objectives of the ESMR was to provide data to map the distribution of polar ice, by providing the first all-weather and all-season means of ice detection. The microwave images produced from the data had a great impact on sea ice research. Zwally and Gloerson (1977) describe the research applications of this imagery. Information concerning ice concentration and ice type within the ice pack can be derived, and temporal changes can be analysed from successive images.

The quality of the ESMR collected data degraded somewhat after 1976, but the U.S. Navy considered it to be reliable enough to use in compiling their operational ice charts until as late as 1980 (Eppler, 1983). One of the main drawbacks to the ESMR was that it only provided information on a single frequency. In order to derive more parameters (i.e., to distinguish between ice types) a multifrequency sensor is needed.

2.1.2 Nimbus-6 and ESMR

The second ESMR to be put into space was on board the Nimbus-6 satellite launched in June 1975. It differed from the Nimbus-5 ESMR (see Table 2.2) in that it operated at the 37 GHz frequency, with dual-polarization (vertical and horizontal) capability. The significant aspects of these changes were that the higher frequency would result in an increase in contrast between first year and old ice, and the dual-polarization would reduce the ambiguity in determining ice type and

TABLE 2.2

ESMR and SMMR Performance Characteristics

	<u>Nimbus-5 ESMR</u>	<u>Nimbus-6 ESMR</u>	<u>Nimbus-7 SMMR</u>
Altitude	1100 km	1100 km	955 km
Swath width	1360 km	1300 km	780 km
Global Coverage	Every 12 hrs.		Every 6 days
Frequency of Operation	Daily	Daily	Alternate days
Field of view	25 km	20° x 43 km	30 km at 0.81 cm to 150 km at 4.6 cm
Wavelengths/ Frequencies	1.55 cm/19.35 GHz	0.81 cm/37 GHz	0.81 cm/37 GHz 1.4 cm/21 GHz 1.7 cm/18 GHz 2.8 cm/10.69 GHz 4.6 cm/6.6 GHz
Polarization	Horizontal	Vertical & Horizontal	Vertical & Horizontal
Incidence Angle	Nadir $\pm 50^\circ$	50°	50.2°
Launch	December 11, 1972	June 1975	October 24, 1978

Sources: Gloersen and Barath (1977), Gloersen and Hardis (1978),
Wilheit (1972), Wilheit (1975), Zwally and Gloersen (1977).

facilitate the quantitative interpretation of radiometric measurements (Wilheit, 1975). In September 1976, the horizontal channel failed, thus reducing the Nimbus-6 ESMR to a single channel sensor. The vertical channel failed about a year after launch, thus ending the life of the sensor. Eppler (1983) states that although the data are potentially useful for sea ice mapping, the data have not been used in polar studies.

2.1.3 Nimbus-7 and SMMR

On October 24, 1978 NASA launched the Scanning Multichannel Microwave Radiometer (SMMR) on board the Nimbus-7 satellite. The SMMR with its five frequencies (37, 21, 18, 10.69, 6.7 GHz) and dual-polarization (horizontal and vertical) system provided a substantial increase in the amount of information available over the previous ESMR's. The resolution of the data equalled that of the ESMR at 30 km (for the highest frequency channel). Table 2.2 outlines the SMMR's performance characteristics and provides a comparison with the two ESMR's. Gloersen and Barath (1977) also provide a summary of the instrument's operating characteristics. Due to power restrictions on board the satellite, the SMMR only operates every other day (Gloersen and Hardis, 1978).

The ability to discriminate between first year and old ice and open water within its field of view, is a significant advancement of the SMMR over the ESMR. The SMMR's multifrequency and dual-polarization characteristics allow for this discrimination (Cavalieri et al., 1984). This ability has specific application to any area containing more than one

type of ice.

In recent years, there have been many sea ice studies involving SMMR data focussing on different regions and different seasons. Some significant ones include Cavalieri et al. (1983), Comiso (1983), Comiso et al. (1984), Svendsen et al. (1983), Cameron (1983), Owens (1983) and Williams (1986). With advanced computer techniques to manipulate satellite data, the amount of retrievable information has increased. With respect to sea ice studies, the overall result has been increased knowledge of sea ice properties.

2.2 Passive Microwave Remote Sensing

The basic principle applied in passive microwave remote sensing is the measurement and interpretation of naturally-emitted radiation from the earth's surface. Passive microwave sensing of sea ice is possible due to the radiometric differences between sea ice and water. This allows for the distinguishing of ice from water within the sensor's field of view. A discussion of the physics of microwave radiation is beyond the scope of this paper. Ulaby et al. (1981) and Ulaby and Garver (1983) discuss the fundamentals of microwave sensing and radiometry. Only the basic aspects relevant to the sensing of sea ice will be discussed here.

2.2.1 Microwave Emissivity

All objects above 0°K emit microwave radiation. The term emissivity refers to the ability to emit this radiation, which depends upon

the composition and the physical structure of the object. Sea ice emissivities vary according to ice type and the frequency being sensed. Figure 2.1 illustrates this variation in emissivity for the major ice types, as reported by Hollinger et al. (1984). The curves were derived from multifrequency measurements made at Mould Bay, NWT and in the Eastern Beaufort Sea. When considering Eastern Canadian Seaboard ice conditions, the ice types of interest are new ice, first year ice and old ice. Emission characteristics of these three ice types therefore need to be outlined.

When discussing emission from sea ice, the depth below the surface from which the radiation emanates is an important consideration. Zwally et al. (1977) define this as skin depth; the thickness of the top layer from which approximately 63% of the radiation emanates. Since emissivity variation among sea ice types is related to skin depth (Gloersen et al., 1973), it is a necessary part of the discussion of emission characteristics from sea ice types.

First year ice, the most prevalent ice type along the East Coast, is characterized by the presence of liquid brine within the ice structure. Vant et al. (1978) report salinities near the ice surface ranging from 5 to 16 parts per thousand. Figure 2.2a summarizes the physical properties of first year ice. The salinity of the ice governs its microwave emission properties. Gloersen et al. (1973) indicate that the skin depth of first year ice is relatively thin, equalling one wavelength or a fraction thereof. For the ESMR and SMMR frequencies concerned (18, 19.35 and 37 GHz), this would range from 1.7 cm to 0.81

FIGURE 2.1

Emissivity vs Frequency Relationship for Sea Ice Types
and Open Water

Adapted from: Hollinger et al. (1984)

FIGURE 2.2a

14

The Physical Properties of First Year Ice

FIGURE 2.2b

The Physical Properties of Old Ice

Source: Vant et al. (1978)

cm. The high salinity of first year ice also causes it to have a high emissivity (~ 0.95), which is almost independent of frequency (Hollinger et al., 1984; Rubinstein and Ramseier, 1985) as illustrated in Figure 2.1.

Old ice may be found along the Eastern Seaboard in small amounts. This ice type has undergone at least one year's melt and therefore has different physical properties from those of first year ice. Figure 2.2b illustrates this fact. Recent studies, e.g., Bjerkelund et al. (1985), have disputed the presence of 'recrystallized ice' layers, and report these layers to consist of snow ice. Vant et al. (1978) report low salinities in multiyear ice, typically less than 1 part per thousand near the surface, due to brine drainage during the melting process. The low salinity results in a much greater skin depth, in the order of several wavelengths (Gloersen et al., 1973). Therefore a greater proportion of the microwave radiation emanates from deeper within the ice. The melting process that multiyear ice has undergone results in the presence of air pockets and other inhomogeneities within the ice (Bjerkelund et al., 1985). These cause volume scattering of the upwelling radiation to occur, which reduces the amount of energy emerging from the surface. As a result, the emissivity of old ice is lower than that of first year, as indicated in Figure 2.1. The sensitivity to volume scattering is directly proportional to the frequency of the radiation (Rubinstein and Ramseier, 1985). Therefore, emissivity decreases with increasing frequency, which is depicted in Figure 2.1.

During the ice growth season along the East Coast new ice forms may be present. New ice, which is generally less than 10 cm thick, is also highly saline, and therefore has a relatively high emissivity, as indicated in Figure 2.1. Initial forms of ice such as frazil and grease ice occur mainly on the water surface and therefore do not exhibit any appreciable thicknesses. The microwave emission in this case is mainly from the underlying water, resulting in a low emissivity (Comiso, 1983). Once ice gets into the nilas stage of growth (5-10 cm thickness) the emissivity increases and becomes distinguishable from that of water.

The emissivity variation between ice types allows for their differentiation using passive microwave remote sensing. The choice of microwave frequencies is dependent upon the emissivity separation of the ice types being sensed. By examining Figure 2.1, it is observed that the ESMR frequency of 19.35 GHz and the SMMR frequencies of 18 and 37 GHz have the widest separation between first year and old ice and open water. Thus it follows that these frequencies are best used for the derivation of ice information.

2.2.2 Brightness Temperature

The amount of radiation emitted by a surface is referred to as its brightness temperature (T_B), expressed in the Kelvin (K) unit of temperature. A surface's T_B is a function of emissivity (ϵ) and physical temperature (T_S), where $T_B = \epsilon T_S$. The radiation sensed at the satellite height has the added effect of an atmosphere, through which the surface radiation must travel. The radiative transfer equation,

depicted in Figure 2.3, takes into account the effects of an intervening atmosphere to the sensed T_B . A detailed description of each of the components is available in Gloersen and Barath (1977) and therefore will not be repeated here. A summary of what each of the terms of the equation represents is presented. The first term in the equation represents the contribution of the surface with an included atmospheric correction component $(e^{-\tau})$. The second term is the upwelling radiation observed after reflection at the surface and transmission back through the atmosphere. The third term represents downwelling atmospheric radiation. The fourth term accounts for space radiation reflected back from the surface, which therefore makes two passes through the atmosphere. The atmospheric correction term $(e^{-\tau})$ is the most important since it takes into account atmospheric attenuation due to the presence of gases and particles. The polar atmosphere is relatively transparent in the frequency range of 19 to 37 GHz (Hollinger *et al.*, 1984), and atmospheric effects can virtually be ignored. The Eastern Canadian Seaboard though is located in the mid-latitudes where atmospheric attenuation is more pronounced. A brief discussion of the causes of attenuation is therefore necessary in order to understand the derivation of the observed T_B .

The three most influential atmospheric constituents are molecular oxygen, water vapour and liquid water droplets, and their effects are discussed by Wilheit (1978). Attenuation due to liquid water droplets is most important at the microwave frequencies used to derive ice information, namely 18 and 37 GHz (Rubinstein and Ramseier, 1985). As

FIGURE 2.3

The Radiative Transfer Equation

- 1 ● SURFACE EMISSIVITY.
- 2 ● REFLECTED DOWNWELLING ATMOSPHERIC RADIATION
- 3 ● UPWELLING ATMOSPHERIC RADIATION.
- 4 ● REFLECTED SPACE RADIATION

$$T_B = \underbrace{\epsilon T_s e^{-\tau}}_{\text{SURFACE EMISSION}} + T_1 + \underbrace{(1-\epsilon)T_2 e^{-\tau} + (1-\epsilon)T_{sp} e^{-2\tau}}_{\text{ATMOSPHERIC CORRECTION TERM}}$$

T_1 IS $\sum \epsilon_i T_{si}$
SMALL
IN POLAR
REGION

ATMOSPHERIC CORRECTION TERM

Adapted from: Ramseler (1983)

indicated by Wilhelm (1978), the absorption coefficient increases with increasing drop size. Precipitating clouds contain the largest drop sizes and therefore provide greater attenuation than either non-precipitating liquid water or water vapour (Gloersen and Barath, 1977). As the Eastern Canadian Seaboard is subject to frequent cloud cover (both precipitating and non-precipitating) during winter months, therefore liquid water droplet attenuation must be considered when deriving ice information from observed T_B 's. Regionally-specific values for total atmospheric opacity (τ), applicable to ESMR and SMMR frequencies, are outlined in Gloersen and Barath (1977) and Swift et al. (1985).

2.3 Sea Ice and Climate

2.3.1 Sea Ice and Atmospheric Interactions

The presence of a sea ice cover affects the heat balance of the atmosphere-ocean system by acting as an interface between the two media. Crane (1981) indicates that the relative distribution of ice and water surfaces represents the most important influence on atmosphere-surface interactions. Figure 2.4 presents a schematic illustration of the atmosphere-ocean energy balance system. Heat energy exchange takes place between the ocean and atmosphere. A sea ice cover acts to insulate the ocean by reducing the latent, sensible and long wave heat flux into the atmosphere (European Space Agency, 1985). Sea ice with its high albedo reduces the amount of solar radiation absorbed at the surface. The amount of open water within the ice pack affects the extent

FIGURE 2.4

The Atmosphere-Ocean Energy Balance System

Source: Lockwood (1979)

to which sea ice can modify this heat exchange. Thus, ice concentration and sea ice area are important variables in studying this relationship.

Feedback mechanisms, as discussed by Kellogg (1975) and Crane (1981) are another way sea ice exerts an effect on the atmosphere-ocean system. The positive feedback role of sea ice can be summarized as follows. A small decrease in temperature increases the extent of the sea ice cover, which results in a higher surface albedo, and a further decrease in temperature, which in turn increases the sea ice cover, and so on. Maykut (1978) indicates that sea ice is an important component in the climatic system because it has the potential to amplify small changes in climate through these feedback mechanisms. Thus sea ice variation becomes an important indicator for detecting climatic change.

2.3.2 Sea Ice Parameters of Climatic Interest

It has been established that sea ice plays an important role in the global climate system. Interannual variability of sea ice conditions as an indicator of climatic change is of principal interest. Zwally (1984) outlines the primary sea ice variables of interest as being geographical extent, concentration (and ice area), and amount of old ice.

Sea ice models have been developed to simulate the behavior of sea ice in real life conditions. Sea ice concentration has been used as a primary variable in certain models for input and verification (Zwally, 1984). Atmospheric General Circulation Models (AGCM's), as discussed by Crane (1981) and Allison (1982), simulate atmospheric circulation over a long period of time to determine climate, and investigate sensitivity to

changes in sea ice conditions. Coupled models combine the conditions and interactions of the ocean and atmosphere to produce a more realistic view of the atmosphere-ocean-ice system. Hibler (1980) provides an outline of sea ice modelling and indicates that early results from coupled circulation models are encouraging in determining the exact role of sea ice in climate.

The European Space Agency (1985) discusses modelling of the polar climate system and points out that the scarcity of polar data makes it difficult to validate these models or choose values for physical parameters. Also outlined are the ice variables for which data are needed for model verification -- extent, concentration, thickness and velocity. Information concerning ice extent and concentration can be derived from passive microwave data. Velocity (derived from changes due to convergence and divergence) can also be inferred by examining successive days of data.

2.3.3 Role of Passive Microwave Data

Satellite-borne remote sensors can provide synoptic information about the polar regions that would be useful for the input and verification of sea ice and climate models. Passive microwave sensors can provide valuable and reliable information about sea ice extent and concentration in this effort. Even though the available satellite passive microwave data set is brief and therefore of limited value for climatic research, it has made substantial contributions to the understanding of sea ice interannual variation (NASA, 1984). Allison (1982)

states that routine monitoring of sea ice from satellites is of highest priority and that passive microwave imagery is the optimal way to observe global ice cover.

Studies using passive microwave satellite data (namely ESMR) have focussed on the relationship between monthly, seasonal and interannual variations in sea ice cover and atmospheric circulation and temperature. Most of these studies have used ESMR (Nimbus-5) data as the basis for investigations. A few notable ones will be described here. Crane et al. (1982) used time lapse film and digital ESMR data to relate annual spatial and temporal changes in sea ice microwave signatures in the Arctic basin to data on atmospheric circulation and surface air temperature. The focus was on synoptic scale processes. Digital ESMR data was also used by Crane (1983) to examine atmosphere - sea ice interactions in the Beaufort/Chukchi Sea and in the European sector of the Arctic. Carleton (1984) examined changes in ice extent and concentration for October 1976 ESMR data in the Western Arctic in relation to synoptic atmospheric events. Cavalieri and Parkinson (1981) and Parkinson and Cavalieri (1982) related Antarctic ice conditions derived from ESMR to atmospheric circulation. Annual and interannual variation in sea ice conditions were the main parameters of investigation.

CHAPTER 3

CHARACTERISTICS OF THE EASTERN CANADIAN SEABOARD

3.1 Definition of the Study Area

For the purposes of this study, the Eastern Canadian Seaboard is defined as the coastal waters stretching from approximately 44°N to 70°N . This region includes the ocean water areas known as the Gulf of St. Lawrence, the East Newfoundland Waters, the Labrador Sea, and the Davis Strait. Figure 3.1 depicts the bounds of the study area and the location of the subregions (which are the focus of analysis in Chapter 5, Section 5.5). The main coastal meteorological stations of interest are also indicated.

The following sections will describe climatic and oceanographic characteristics of the Eastern Canadian Seaboard. The descriptions will be restricted to the winter time period, which is the season of ice growth.

3.2 Climate

3.2.1 Air Temperature

The lowest mean winter temperatures occur in the December to February time period on the Canadian East Coast. Figure 3.2 presents mean and extreme monthly air temperature data for various stations and regions along the Eastern Seaboard. The December to March period is

FIGURE 3.2
Eastern Canadian Seaboard Air Temperature Statistics

Source: Mortsch et al. (1985)

characterized by below 0°C air temperatures, which contribute to the growth of sea ice. Markham (1980) indicates that in the Gulf of St. Lawrence and Newfoundland Waters areas the mean temperatures during winter do not fall very far below the freezing point. The result is that abnormally cold and mild winters can have a greater effect on the degree of ice growth in this region, than in more northern regions.

The accumulation of freezing degree days (FDD) can be used as an indicator of the coldness of a winter. A freezing degree-day is defined as the departure of the daily mean air temperature by one degree below the freezing point (Markham, 1980). Two days with daily means of -10°C would correspond to an accumulation of 20 freezing degree days. Average FDD accumulations to the end of February for the following meteorological stations indicate the range for the Eastern Canadian Seaboard: St. John's - 362.6, Hopedale - 1413.3, and Cape Hooper - 2969.3 (Environment Canada, 1982).

3.2.2 Air Pressure

During the winter months, the East Coast is under the influence of the Icelandic Low, normally located between Iceland and Greenland. Bursey et al. (1977) report surface pressures of less than 100 kPa for this low during the month of January. Figure 3.3 exhibits the surface pressure distribution for the month of January, typical of winter conditions. As with all lows in the Northern Hemisphere, circulation is in a counter-clockwise direction around the low. The prevailing wind direction is thus northwesterly for the East Coast region. In general, areas

FIGURE 3.3

Typical Winter Surface Pressure Distribution for Eastern Canada

Source: Gustajtis (1979)

of low pressure are characterized by stormy and unsettled weather, and the East Coast is no exception. During the winter months (January to March), over 50% of the time, the East Coast is totally obscured by cloud cover (Gustajtis, 1979).

The position of the Icelandic Low can vary from year to year. Bursey et al. (1977) report that the centre of this low ranged from near Spitsbergen (in the Greenland Sea) to Newfoundland during the 1970's. This variability can affect the circulation pattern governing the Eastern region, which can in turn influence the sea ice regime.

3.2.3 Winds

The winter pressure pattern over the East Coast results in a prevailing northwesterly wind flow. Figure 3.4 illustrates the typical winter distribution of wind velocities along the East Coast. The strongest winds are encountered in the winter months. Bursey et al. (1977) report that during the months of December to March, over 50% of the wind speed observations are 22 knots (~40 km/hr) and greater. Surface winds influence the location and distribution of ice (Markham, 1980), and increased wind strength augments this influence.

3.3 Oceanography

Gustajtis (1979) has described the oceanographic characteristics of the Eastern Canadian Seaboard, with particular reference to the Labrador Sea. The relevant aspects with respect to the sea ice regime are summarized here.

FIGURE 3.4

Typical Winter East Coast Wind Velocities

Source: Mortsch et al. (1985)

3.3.1 Currents

The Labrador Current is the major feature of the ocean circulation along the East Coast. As illustrated in Figure 3.5, the origin of the current is in the area of 60°N , where the West Greenland Current offshoot and the Baffin Island, or Canadian, Current converge.

The West Greenland Current, which is the major contributor to the Labrador Current (Lazier, 1980), is relatively warm and remains ice-free as far north as 67°N . North of 60°N a branch of this current flows westward, and becomes part of the Labrador Current. The Canadian Current, consisting of cold Arctic water, flows southward along the eastern Baffin Island coast. At Hudson Strait one arm flows west and eventually joins the outflowing current from the strait. The other arm flows south across the strait to form the Labrador Current. Thus the Labrador Current receives its energy from the flows of the two currents described above and the outflow from Hudson Strait.

The Labrador Current is divided into two streams. The inshore stream is confined to the continental shelf and contains cold polar water. The offshore stream is much warmer with its origin from the West Greenland Current. Stein (1982) refers to these two streams as the polar component and the Irminger Current, respectively. The Labrador Current travels south along the Labrador and Newfoundland coasts, where it divides into two branches in the Grand Banks region. Lazier (1980) reports that surface current velocities for the main Labrador Current range from 35 to 40 cm/s.

In the Gulf of St. Lawrence the main flow of water is from the St.

FIGURE 3.5

Major Ocean Currents Along the Eastern Canadian Seaboard

Lawrence River southeastward to the Cabot Strait (Atmospheric Environment Service, 1982). The Gaspe Current and the Cape Breton Current form the outward flow of water from the Gulf. Two inward-flowing currents travel up the western coast of Newfoundland and along the southern coast of Anticosti Island, respectively.

3.3.2 Sea Surface Temperature

Typical winter sea surface temperatures are portrayed in Figure 3.6. The isotherms represent mean conditions for the time period 1855 to 1984, derived from data collected by ships-of-opportunity (Mortsch et al., 1985).

3.4 Sea Ice Regime

Sea ice begins forming in the Eastern Canadian Seaboard region as soon as temperatures fall below freezing. Formation starts in the northernmost region of the study area first, with ice spreading through Davis Strait during the month of November. During December the ice spreads rapidly down the Labrador Coast, to reach the Strait of Belle Isle by the end of the month. The months of January and February are characterized by southward growth in the East Newfoundland Waters and Gulf of St. Lawrence regions. Seaward expansion continues in all other regions. Maximum ice extent is usually attained in the late February to mid-March period, depending upon the severity of the winter. In late March the ice begins its retreat northward, a trend which continues until the beginning of August, when the Eastern Canadian Seaboard is

FIGURE 3.6

Typical Winter Sea Surface Temperatures Along the
Eastern Canadian Seaboard

Source: Mortsch et al. (1985)

virtually ice-free again.

3.4.1 Ice Characteristics

Sea ice along the Eastern Seaboard is primarily first year ice. Level pack ice can reach thicknesses up to 150 cm (Atmospheric Environment Service, 1982), although ridging may create greater thicknesses. The drift of ice from northern regions accounts for large thicknesses. Generally ice thicknesses increase from south to north in the study area, due to the longer ice growth seasons. The continual movement of the pack, due to winds and currents, causes ice to be broken and rejoined several times, resulting in pieces of varying sizes and thicknesses to be present (Skidmore, 1979). Divergence and compression take place in response to wind speed and changes in direction. Divergence, due to offshore blowing winds, creates open water leads between ice floes, while compression, due to onshore blowing winds, solidifies the pack.

Throughout the winter, new ice forms are present, especially in the ice margin region. New ice, which is generally less than 10 cm thick (Atmospheric Environment Service, 1980), takes the form of grease ice or nilas. This stage of ice development also has a high salinity. New ice can also form within the pack, between ice floes, after divergence has taken place.

Old ice, which has survived more than one year's melt, may be present within the East Coast pack. The origin of this ice is the more northern Arctic regions. Markham (1980) estimates the amount of old ice

present to be approximately 10% of the total pack. During colder than usual summers, ice may survive melt periods in northern regions such as Baffin Bay and Foxe Basin. Flöes of old ice can therefore drift down the Eastern Canadian Seaboard and become mixed with the pack ice of the following winter. The Atmospheric Environment Service (1982) reports that thicknesses of old ice along the Labrador Coast have been measured up to 210 cm.

3.4.2 Factors Determining Ice Extent

The maximum extent to which the sea ice cover grows each year along the Eastern Seaboard is a function of several factors, some of which are interdependent. Markham (1976) discusses the variability of ice seasons along the Canadian Eastern Seaboard and indicates that the key factors which affect the severity of the seasons are air temperature, winds and water currents.

Below-freezing air temperatures initiate the growth of ice, and the length of time which they stay below 0°C ensures the continued production of new ice and allows extent to increase. The windflow controls the movement of the ice and determines how dispersed or compressed the ice cover will be. The relative coldness or mildness of the wind is related to the characteristics of its source (e.g., Arctic). In this way, air temperature and wind are interdependent.

Ocean currents, particularly the Labrador Current, influence the movement of the sea ice cover down the East Coast, but their sea surface temperatures determine formation of ice. The Labrador Current can vary

in temperature, which exerts an effect on ice growth in the region. Markham (1976) reports that in the early part of 1973 the Labrador Current was abnormally cold, which permitted more ice to form, and earlier than usual, along the Labrador-Newfoundland coast. Schell et al. (1975) discuss the effect of increased water volume transport from the West Greenland Current, which would result in higher Labrador Current water temperatures. This would inhibit the growth of ice and limit its spatial extent.

Atmospheric circulation also influences ice extent along the Eastern Seaboard. Barry (1980) indicates that the overall pattern of ice extent in the Northern Hemisphere is strongly influenced by interactive oceanic and atmospheric circulations. The atmospheric pressure pattern controls the flow of air within the region, thus affecting the winds and air temperatures.

The position of the Icelandic Low in winter controls the atmospheric circulation in the Eastern Seaboard region. The interannual variability of the Low's position has been noted by several authors (Markham, 1976; Bursey et al., 1977; Johnson, 1980) with corresponding effects on ice extent. Markham (1976) reports on an analysis of pressure charts for light and heavy ice years, 1960 and 1973 respectively. In 1960 the Icelandic Low was displaced south, resulting in a restricted Eastern Seaboard ice cover due to a northeasterly air flow. In 1973 the position of the Low provided a cold northwesterly flow from the Arctic, which resulted in an extensive ice cover. Johnson (1980) indicates that the displacement of the Icelandic Low to the northeast

results in greater than normal ice extent in the Arctic. From analyses of 25 years of pressure data, Johnson concludes that regional extremes in sea ice are associated with the intensification of the closest major low pressure centers and troughs.

CHAPTER 4

ANALYSIS OF INTERANNUAL SEA ICE VARIATION

4.1 Format of the Passive Microwave Data

The Nimbus-5 ESMR and Nimbus-7 SMMR data are stored on computer tapes. The basic format of these tapes consists of brightness temperatures (T_B 's) stored for each beam position. The SMMR tape product used in the Eastern Seaboard analysis is the CELL-ALL tape, which contains vertical and horizontal polarization T_B 's and seasonal geographic filters for each of the five channels, grouped into combinations of cells and bands equaling 780 km^2 (Gloersen and Hardis, 1978). Location coordinates are given for each cell and band. The computer tapes are archived at the National Space Science Data Center (NSSDC) at the NASA Goddard Space Flight Center, Greenbelt, Maryland. A Canadian archive of tapes exists at Ice Research and Development (AES), York University, North York, Ontario.

The set of ESMR and SMMR data tapes that were available for this analysis unfortunately include a data gap covering the 1978 winter season. U.S. Navy ice charts, which are compiled from ESMR data (Eppler, 1983), became the source of 1978 ice information for the inter-annual variation analysis. The U.S. Navy utilizes data processed from the National Oceanic Data Distribution System (NODDS). Comparisons between NODDS data and data processed by NASA have shown that there is

no significant difference between the two products (Williams, 1986).

4.2 Sea Ice Algorithms

In order to derive sea ice information from the archived T_B data, computer-based algorithms must be applied to the data. Sea ice concentration is the desired parameter, which refers to the percentage of an ocean area covered by ice (Zwally, 1984). For the Eastern Canadian Seaboard analysis, sea ice algorithms specific to ESMR and SMMR were utilized in order to derive ice concentrations and ice edge positions. Constants used in these algorithms were also derived specific to the East Coast region. The algorithms used are discussed in the following sections.

4.2.1 Simple Linear Algorithm

Since the ESMR is a single frequency sensor, a simple linear algorithm is used to derive ice concentration. The basic operation of the algorithm involves deriving a percentage value for ice concentration from an observed T_B through a linear interpolation between characteristic radiances (T_B 's) of open water (0% ice) and 100% sea ice cover (Gloersen et al., 1974). Figure 4.1 expresses this algorithm graphically. Using the linear relationship assumed by this algorithm, an area of 50% ice cover would have an observed T_B halfway between that of open ocean and fully consolidated ice. For the Eastern Seaboard analysis, the T_B constants for open water and 100% ice were derived specific to the East Coast region. As indicated in Figure 4.1, the characteristic

FIGURE 4.1
The Simple Linear Algorithm

Source: Ramseier (1983)

T_B for open water at 19.35 GHz is ~ 135 K while first year ice is ~ 235 K.

The value produced using the simple algorithm is a total ice concentration, meaning that ice type (i.e., first year or old) is not differentiated. The single frequency and polarization nature of the ESMR data prevents direct separation of ice type, although Gloersen *et al.* (1978) report that in certain seasons and locations relative amounts of first year and old ice can be estimated. Since first year ice is the predominant ice type on the East Coast, this limitation of the algorithm is not significant. Thus, it can be assumed that the total ice concentration value approximates a concentration of first year ice.

Another limitation to the algorithm concerns the effect of ocean roughness. Wind blowing across the ocean surface creates roughness and foam. Wilheit (1978) discusses the effects of a rough ocean state on microwave sensing. Generally, roughness and foam cover increase the ocean surface emissivity, and hence the observed T_B as illustrated in Figure 4.2. When this higher than normal observed T_B is used as input into the simple linear algorithm a false ice concentration will be produced, thus deceptively implying the presence of ice in open ocean. For example, Comiso and Zwally (1984) state that the T_B of areas with ice concentrations 25% and lower often equals those of ice-free regions, where extreme surface conditions (e.g., foam and roughness) are present. Since storm activity, which creates rough ocean states, is a common feature of winters on the Eastern Canadian Seaboard, careful interpretation must be made of the ice concentrations produced from passive microwave data. Owens and Ramseier (1984) report, from an analysis of East

FIGURE 4.2

The Increase in T_B at 19.35 GHz Caused by Wind Speed
Over an Ocean Surface

Source: Wilheit (1978)

Coast ESMK ice maps, that the erroneous ice concentrations produced due to storm activity average around 10%. Based on knowledge and experience in the East Coast region, a person can ignore erroneous ice concentrations. Unfortunately, with the single frequency data it is impossible to remove the rough ocean effect from the T_B data. As discussed by Wilheit (1978), multifrequency data is needed to overcome this limitation, and has been successfully done with the SMMR data (Rubinstein and Ramseier, 1985; Rubinstein et al., 1985).

4.2.2 AES/Ph.D. Algorithm

The AES/Ph.D. algorithm was developed and tested specifically with Nimbus-7 SMMR data. Using two of the SMMR frequencies, 18 and 37 GHz; the capability is present to differentiate between two ice types, namely first year and old ice. Thus, the algorithm produces ice concentration values for first year ice and old ice, as well as total ice values (Rubinstein et al., 1985). Rubinstein et al. (1985) and Rubinstein and Ramseier (1985) outline the development of this algorithm. The basic feature of the model is multi-step filtering, which removes the effects of cloud, wind and precipitation. A flowchart representation of this aspect is presented in Figure 4.3. The aim of the filtering technique is to prevent ice edge distortions due to rough ocean or weather; a limitation that affected the single frequency ESMR data. The algorithm uses regionally-specific inputs (constants). Thus for the Eastern Seaboard analysis constants were utilized specific to the East Coast region and its ice conditions.

FIGURE 4.3

The AES/Ph.D. Algorithm

Source: Rubinstein and Ramseier (1985)

The operation of this algorithm is computer-based. At each SMMR cell location the T_B is tested in order to determine if the source of the microwave emission is from an ice-covered area or due to rough sea or weather conditions. The filters then remove any atmospheric or wind effects, with the final output being total ice concentration and the ice type fractions, as illustrated in Figure 4.3.

The AES/Ph.D. algorithm has been tested operationally for selected regions, the Eastern Canadian Seaboard being one of them. Moreau *et al.* (1985) report on the validation of algorithm results for East Coast ice conditions against Atmospheric Environment Service ice charts. Preliminary results indicate ice concentration agreement to $\pm 10\%$ and ice edge agreement to ± 15 km.

4.3 - Display of the Ice Concentration Data

The ice concentrations produced using the previously described algorithms can be contoured and mapped onto a geography overlay using specialized computer software (Thirkettle, 1985). The presentation of the ice information in map format allows a user to visually examine the spatial extent of the sea ice cover and the pattern of ice concentration.

The system involved in processing the passive microwave data is described in Thirkettle (1985) and summarised here. Before the T_B 's are converted into ice concentrations, the data is remapped onto a subset of the Canadian Meteorological Centre (CMC) 381 km square grid, using a weighted averaging technique. For the Eastern Canadian Seaboard

analysis a 1/10 CMC grid was employed, where each grid square measures 38.1 x 38.1 km. This is slightly larger than the size of one ESMR or SMMR footprint. The next stage involves applying the ice concentration algorithm to the reduced data set. Contouring software allows the ice concentration data to be summarized according to specific percentage concentration levels. For the East Coast analysis the levels 10%, 15%, 35%, 65%, 85% and 99% were utilized. Mapping routines then position the ice information onto the physical map at the specified projection and scale. For the East Coast analysis a 1:5,000,000 polar stereographic map was used. Figure 4.4 presents an example of the format of the map (at a reduced scale) used in this analysis.

4.4 Analysis Methodology for Interannual Variation

4.4.1 Dates of Maximum Ice Extent

The first stage in the analysis of interannual variation in maximum ice extent involved determining approximate dates of maximum extent for each year from 1973 to 1985. Archived ice charts at the Ice Climatology and Applications Division of the Atmospheric Environment Service provided the source of this information. By examining the charts visually for each ice season, the time period of maximum spatial extent for the entire study area was narrowed down. Using these dates as a guide, passive microwave data covering a period of several weeks were processed in order to ensure coverage of maximum extent. Because the Nimbus-7 SMMR only operates every second day and due to its orbital configuration, 3 days of data were needed in order to get complete

48

22 FEB 1981 06:15
JAN 27 1981 06:15
JAN 27 1981 06:15

coverage of the Eastern Canadian Seaboard. The resulting ice map was therefore an average of 3 SMMR days, which approximately corresponds to a weekly (~6 days) average. Since complete coverage is available with one day of ESMR data, a single daily average for each week in the specified time period was utilized.

For each year in the time series, the ice maps were overlaid in order to determine which map contained the maximum spatial extent of ice. Appendix A.1 contains the maps expressing the maximum ice extent for each year, 1973 to 1985. The 15% concentration contour line was used to represent the ice edge position. A summary overlay was produced containing the maximum ice edge location for each year from 1973 to 1985, which is a total of 13 ice edges. Visual examination of this overlay yielded information on which areas of the Eastern Canadian Seaboard experienced the most variation during the 13-year period. The East Newfoundland Waters and Davis Strait regions are the most variable in terms of maximum ice extent, where the difference between extreme maximum positions of the ice edge range from 500 to 600 km, while variation along the Labrador Coast is not as great, ranging from 150-300 km. The Gulf of St. Lawrence exhibits variation of the order of 200 km. These measurements were obtained directly from the overlay, mainly parallel to lines of latitude, and along the main axes of ice growth. Figure 4.5 exhibits extreme positions of maximum ice extent from 1973 to 1985. Each line is a composite of extreme extents for each region, therefore they do not represent one single ice season. Although, the

FIGURE 4.5

50

Extremes in Maximum Ice Extent Position (1973-1985)

minimum extreme position follows closely to the 1978 and 1981 seasons for the total Eastern Canadian Seaboard. The maximum extreme is a composite of 1975, 1983, and 1985 positions for the Gulf, Davis Strait and East Newfoundland Waters respectively.

4.4.3 Quantitative Analysis

In order to analyse the maximum ice extent data quantitatively, statistics were generated for two parameters -- ice extent and ice area. Zwally (1984) discusses the importance of these two parameters in the study of sea ice variability. Sea ice extent refers to the area of ocean covered by ice, i.e., spatial coverage of ice. Sea ice area takes into account the distribution of ice concentration within the pack. Therefore the difference between ice extent and ice area equals the amount of open water within the pack. If ice extent and ice area were equal, then the ice pack would be 100% compact ice. Therefore the combination of these parameters gives two sources of information -- ice coverage and compactness. The climatic significance of ice area and extent were discussed previously in Chapter 2. The methodology used to derive these parameters is outlined below. The approach to statistics derivation and display of results follows closely that employed by Zwally et al. (1983) in their study of Antarctic ice extents from ESMR data.

4.4.3.1 Methodology of Statistics Derivation

The 1/10 CMC grid is used as the basis for deriving the ice area and extent statistics. Each 38.1 km square grid cell measures 1451.61

km² in area. Total ice extent (IE) can be calculated by summing the number of grid squares containing ice (N) and multiplying by 1451.61 km², thus $IE = N \times 1451.61 \text{ km}^2$. Ice area is computed using the ice concentration derived for the grid square. By multiplying the concentration (C%) by the grid square area (1451.61 km²), a value for the area (A_n) of that grid square covered by ice is achieved. The total of the ice areas ($\sum A_n$) for all the grid squares containing ice is therefore the total ice area (IA) value for the Eastern Seaboard. Thus $IA = \sum A_n$ where $A_n = C\% \times 1451.61 \text{ km}^2$.

If IE and IA are calculated for each year in the study period (1973-1985), trends over time for the two parameters are yielded, which can be expressed graphically. These trends represent interannual variation in maximum ice conditions for the Eastern Canadian Seaboard, and can be compared to trends in climatic parameters (Chapter 5).

4.4.3.2 Computer and Manual Statistics Generation

A mainframe computer can facilitate the derivation of the ice area and extent statistics. The SMMR data is suited to this type of manipulation. The ESMR data, on the other hand, is not suited because of the false ice concentrations produced due to rough sea state. The computer cannot distinguish between real and false concentrations; hence errors in the derived ice area and extent values could result with the input of false ice information. A manual method of derivation became the solution to this problem.

An overlay was produced containing the 1/10 CMC grid configuration.

By overlaying this grid on the maps containing the ice concentration contours, ice extent and ice area can be derived. The number of squares contained in each contour level were counted and the sum then multiplied by 1451.61 km^2 and the average concentration for the level. For the concentration levels 15-34.9%, 35-64.9%, 65-84.9%, 85-98.9% and 99-100%, the average concentrations used were 25%, 50%, 75%, 92% and 100% respectively. The ice areas derived for each contour level were then summed to yield a total ice area value for the entire study area. The total ice extent value is calculated by multiplying the total number of grid squares for all concentration levels by 1451.61 km^2 . This manual method was used for each year of ESMR data (1973-1978). The list of generated statistics appears in Appendix A.2.

Since average concentrations are used in the manual derivation process, the resulting ice extent and ice area values will deviate slightly from true conditions. The computer-generated statistics will be closer to reality as the ice concentrations from the 38.1 km^2 grid are used in calculations. At each grid cell the derived ice concentration from the SMMR data is stored in a computer file for future statistical analyses. Computer generation of statistics involves calculating and summing ice areas from the grid cells, with the final output being values for total ice area and extent for the Eastern Canadian Seaboard. The computer-generated statistics for the SMMR data (1979-1985) are listed in Appendix A.2.

In order to validate the manual method, it was used for selected

SMMR dates and compared to the computer-generated results. The manually-generated ice areas and extents averaged 7.2% and 7.4% (with all values less than 10%) lower than the computer-generated values respectively. This difference was deemed acceptable and the manually-generated statistics could therefore be used with the computer-generated ones to produce an overall trend (1973-1985).

4.4.3.3 Trends in Ice Area and Extent

The trends in ice area and ice extent produced from the ESMR and SMMR statistical analyses are graphed in Figure 4.6. Table 4.1 lists the corresponding ice area and extent values with maxima and minima for the period highlighted. Interannual variation in maximum Eastern Canadian Seaboard ice conditions (1973-1985) is evident in the graph. Ice extent and ice area exhibit similar trends with generally decreasing values from 1973 to 1979, followed by consistently low values to 1981. After 1981 an increasing trend is noted with a maximum in 1984, followed by a decrease.

The variation in amount of open water within the Eastern Seaboard ice pack is also evident in Figure 4.6 as the difference between the two curves. The variation ranges from 20%-30% of total ice extent over the time period. The year 1978 exhibits the most compact conditions, while 1981 exhibits the least. In terms of actual amount of open water, 1978 exhibits the smallest area while 1975 exhibits the greatest.

4.5 Validation of Ice Area and Extent Trends

Before proceeding with any climatological analysis of the trends in

FIGURE 4.6

TABLE 4.1

Eastern Canadian Seaboard Maximum Ice Extent and Area Values (km²)
(1973-1985)

	1973	1974	1975	1976	1977
IA	997683.86 (Feb. 19)	899707.88 (Feb. 28)	929719.92 (Feb. 25)	911226.41 (Feb. 29)	780029.89 (March 9)
IE	1289755.50 (Feb. 19)	1263626.50 (Feb. 21)	1312981.20 (Feb. 25)	1259997.50 (Feb. 29)	1015401.20 (March 5)
	1978	1979	1980	1981	1982
IA	766481.31 (Feb. 14)	620307 (March 9)	608859 (March 9)	558026• (Feb. 22)	725331 (March 17)
IE	950078.75 (April 4)	958063 (March 9)	898547 (March 9)	868063• (Feb. 22)	1037901 (March 17)
	1983	1984	1985		
IA	915284 (March 26)	1003933* (Feb. 15)	814942 (March 13)		
IE	1252739 (March 26)	1335481* (Feb. 21)	1188869 (March 7)		

Mean Ice Area (1973-1985) = 810117.79 km²
 Standard Error = ± 41329.20 km²
 Mean Ice Extent (1973-1985) = 1125500.28 km²
 Standard Error = ± 48037.08 km²

* 1973-1985 Maximum

• 1973-1985 Minimum

IE = Total spatial extent of ice

IA = Total area of ice (IE minus amount of open water)

ice area and extent, the values had to be validated through comparison to a conventional sea ice data source. British Meteorological Office ice charts were used for this purpose since they provide ice information (position, state and concentration) about the entire Eastern Canadian Seaboard. These charts, at a scale of 1:21,597,000, are produced at the end of each month based on information from a variety of sources including Atmospheric Environment Service composite ice charts, and they cover the northern hemisphere polar region. Figure 4.7 shows a reduced portion of one of these charts illustrating Eastern Canadian Seaboard ice conditions for the end of February 1984.

Using the manual method described in Section 4.4.3.2 and an overlay of 68.6 km grid squares, values for ice extent and area were derived from the closest corresponding British charts to the ESMR and SMMR dates. Figure 4.8 illustrates graphically these trends and provides a comparison to the ESMR and SMMR trends. Correlation coefficients, for a sample size of $n = 11$, were generated in order to compare these trends statistically. The trends in ice extent exhibit the best correlation with an r -value of 0.91, while the ice area trends have an r -value of 0.77. These values were tested and found to be statistically significant. From this comparison, it was concluded that the passive microwave ice area and extent trends (1973 to 1985) are reasonably valid estimations of actual ice conditions.

Saulesleja and Phillips (1982) examine maximum ice extent along the Canadian East Coast and report that the early 1970's were above normal

FIGURE 4.7

58

Example of Eastern Canadian Seaboard Portion of a
British Meteorological Office Ice Chart (February 1984)

FIGURE 4.8

Maximum Ice Extents and Areas from British Meteorological Office (BMO)
Ice Charts as Compared to Passive Microwave Trends (1974-1984)

ice years. The values indicated in Figure 4.6 reflect this fact. They also illustrate a decrease in ice extent after 1976, which corresponds to the trend derived from the passive microwave data. Thus it can be concluded that the trend in maximum ice extent for 1973 to 1985 expressed in Figure 4.6 is a reasonably valid one.

CHAPTER 5

EXPLANATION OF SEA ICE INTERANNUAL VARIATION

5.1 Introduction

In order to account for the interannual variation of maximum ice extent and area along the Eastern Seaboard, one must look into the climatological and oceanographic state of the area over the time period of interest (i.e., 1973-1985). This chapter will investigate the significance of the ice area and extent trends derived from the passive microwave data through comparisons to several climatological and oceanographic parameters. The climatological parameters investigated are air temperature, freezing degree day accumulations, winds and the position of the Icelandic Low. The main oceanographic parameter is sea surface temperature. Ocean currents are not examined due to the lack of available data on interannual variability of current characteristics. The aim of this effort is to explain why this variation is observed, and, if possible, isolate any controlling mechanisms.

The comparisons will mainly be quantitative, but in some cases qualitative analyses can only be used. The quantitative comparisons consist of calculating correlation coefficients (r -values) for each sample (size = n) and then testing them for significance, according to the procedures outlined by Hammond and McCullagh (1978). The correlation coefficient indicates the degree of association between two

variables, and the testing procedure determines whether or not any observed association could be due to random variations.

5.2 Climatological Parameters

5.2.1 Air Temperature

As discussed in Chapter 3, Section 3.4.2, air temperature plays a role in the production and growth of sea ice along the Eastern Seaboard. Generally, below-freezing air temperatures promote ice growth. The length of time temperatures remain below 0°C , and their severity, will contribute to the amount of ice produced and the spatial extent to which the cover grows. Air temperature can vary from year to year; thus the effect on ice seasons can vary from year to year. In order to investigate the relationship between air temperature and the trend in ice area and extent observed from 1973 to 1985, air temperatures from coastal meteorological stations along the Eastern Seaboard were analysed for this time period.

February and March monthly mean air temperatures were first investigated since these months represent the time at which maximum ice extent occurs. The air temperature means for the study area are listed in Table 5.1, while the individual station temperatures can be found in Appendix A.3. Figure 5.1 graphically compares ice extent and area to the February and March monthly means. The air temperature means can be described generally as being erratic and they do not follow as clear a pattern as the sea ice trends. Correlation coefficients were calculated in order to determine the degree of association between the monthly air

TABLE 5.1

Eastern Canadian Seaboard February and March Mean Air Temperatures (°C)
(1973-1985)

	<u>1973</u>	<u>1974</u>	<u>1975</u>	<u>1976</u>	<u>1977</u>	<u>1978</u>	<u>1979</u>
February	-14.9	-13.1	-16.4	-12.0	-13.0	-10.7	-16.1
March	-11.0	-12.3	-11.2	-9.2	-8.2	-13.1	-8.6
	<u>1980</u>	<u>1981</u>	<u>1982</u>	<u>1983</u>	<u>1984</u>	<u>1985</u>	
February	-12.0	-11.2	-16.2	-9.3	-11.5	-16.9	
March	-9.2	-6.8	-12.4	-11.7	-11.0	-10.8	

Source: Data archived at Environment Canada's Ice Centre in Ottawa.

FIGURE 5.1
Trends in Ice Area and Extent Compared to February and March
Mean Air Temperatures (1973-1985)

temperature means and the ice values. These are listed below:

February Temp. Mean vs. Ice Area =	0.0236	(n = 13)
February Temp. Mean vs. Ice Extent =	-0.1045	(n = 13)
March Temp. Mean vs. Ice Area =	-0.5324	(n = 13)
March Temp. Mean vs. Ice Extent =	-0.4526	(n = 13)

The testing of these values indicates that there is little association between the February monthly mean temperatures and ice area and extent, and also between March temperature and ice extent. Their r-values were not significant at the lowest acceptable confidence level (95%). The correlation with ice area shows a slightly higher negative r-value which when tested is significant at the lowest acceptable confidence level (95%). The March mean temperature pattern therefore shows a weak association with the trend in ice area. The negative value indicates that an increase in ice area corresponds to a decrease in air temperature.

The same approach was applied using a 'seasonal' mean instead of a monthly mean. A seasonal mean takes into account air temperature characteristics during the period of ice growth up until the time of maximum extent. Jacobs and Newell (1979) use this approach for Davis Strait and Baffin Bay ice conditions. The December to February time period was chosen as representing the 'winter season' since, on average, maximum ice extent is attained at the end of February. This time period is also consistent with that used by Jacobs and Newell (1979). December, January and February monthly air temperature means for coastal meteorological stations were averaged, the result being a representative seasonal mean. Table 5.2 lists the average seasonal means for the study area for 1973 to 1985. The individual seasonal means for the meteorolo-

TABLE 5.2

Eastern Canadian Seaboard Seasonal Air Temperature Means (°C)
(December-February, 1973-1985)

<u>1973</u>	<u>1974</u>	<u>1975</u>	<u>1976</u>	<u>1977</u>	<u>1978</u>	<u>1979</u>
-14.3	-12.4	-14.1	-12.6	-10.9	-11.0	-10.8
<u>1980</u>	<u>1981</u>	<u>1982</u>	<u>1983</u>	<u>1984</u>	<u>1985</u>	
-10.5	-10.9	-11.6	-13.5	-13.0	-10.4	

Source: Data archived at Environment Canada's Ice Centre in Ottawa.

gical stations used are tabled in Appendix A.3. Figure 5.2 exhibits the trend in the seasonal air temperature mean as compared to the trends in ice area and extent. The seasonal air temperature curve follows a similar pattern as the ice curves, with the coldest temperatures corresponding to periods of high maximum ice extent. Correlation coefficients (r-values) calculated for these curves are listed below:

Seasonal Temp. Mean vs. Ice Area = -0.8189 ($n = 13$)
 Seasonal Temp. Mean vs. Ice Extent = -0.8159 ($n = 13$)

These values were tested using the correlation test formula from Hammond and McCullagh (1978) and found to be significant at the highest (99.9%) confidence level. Thus, it can be concluded that there is a significant (correlation) association between the December to February seasonal air temperature mean and maximum ice area and extent during the 1973 to 1985 time period. The negative correlation indicates that decreasing seasonal air temperature corresponds to increasing ice area, and vice versa.

5.2.2 Accumulated Freezing Degree Days

Accumulated freezing degree days (FDD's) are related to air temperature as outlined in Chapter 3, Section 3.2.1. The FDD accumulations are representative of the amount of freezing which has taken place throughout the season. The relationship between FDD's and ice conditions has been investigated and reported in the literature beginning with Zubov (1945). More recently, Bitello (1961) has derived equations relating FDD's to growth and decay of ice thickness in the Canadian

FIGURE 5.2
Trends in Ice Area and Extent Compared to Seasonal Air Temperatures
(1973-1985)

Arctic Archipelago. The significance of FDD's to ice growth indicates that there may be a relationship with spatial extent of ice as well. Therefore it was decided that FDD's should be examined for the Eastern Seaboard as part of accounting for sea ice maximum extent interannual variability.

FDD accumulations to the end of February (average time of maximum ice extent) for coastal meteorological stations were averaged to produce a mean value for the Eastern Canadian Seaboard. Table 5.3 lists these values for each year from 1973 to 1985. Individual station accumulations are tabled in Appendix A.3. Figure 5.3 expresses graphically the trend in mean FDD accumulations as compared to the variation in ice area and extent. The pattern in the FDD curve is similar to the ice curves, with highest FDD accumulations corresponding to maxima in ice area and extent. Correlation coefficients for the curves are listed below:

FDD Accumulation vs. Ice Area = 0.7853 (n = 13)

FDD Accumulation vs. Ice Extent = 0.7823 (n = 13)

These r-values were tested and found to be statistically significant at the 99.5% confidence level. Thus, Eastern Canadian Seaboard FDD accumulations (to the end of February) are significantly associated with ice area and extent along the Eastern Canadian Seaboard for the period 1973 to 1985. The positive correlation indicates increases in FDD's correspond to increases in ice area and extent values, and vice versa.

5.2.3 Position of the Icelandic Low

The relationship between the interannual variation in the position of the Icelandic Low and variations in ice extent has been investigated

TABLE 5.3

FDD Accumulations for the Eastern Canadian Seaboard to the End of
February (1973-1985)

<u>1973</u>	<u>1974</u>	<u>1975</u>	<u>1976</u>	<u>1977</u>	<u>1978</u>	<u>1979</u>
1642.7	1258.4	1525.9	1418.0	1255.6	1259.6	1324.7
<u>1980</u>	<u>1981</u>	<u>1982</u>	<u>1983</u>	<u>1984</u>	<u>1985</u>	
1203.3	1257.7	1207.4	1543.6	1566.1	1340.1	

Source: Data archived at Environment Canada's Ice Centre in Ottawa.

FIGURE 5.3

Trends in Ice Area and Extent Compared to Eastern Canadian Seaboard
FDD Accumulations (1973-1985)

and documented. As discussed in Chapter 3 (Section 3.4.2) the direction of displacement of the Icelandic Low exerts an influence on ice extent in the Eastern Arctic. Johnson (1980) indicates that Arctic sea ice is of greater extent than normal when the Icelandic Low is stronger and displaced to the northeast. As reported by Van Loon and Madden (1983), the Low tends to move east as it moves north, and as it moves south it also moves west. The movement of the Icelandic Low to the southwest results in mild winters for the Eastern Arctic due to warm air advection over Greenland (Rogers, 1985). Based on the results of these investigations, the examination of Icelandic Low interannual variability over the 1973 to 1985 time period is a necessary component in accounting for the interannual variability seen in ice extent and area.

Figure 5.4 exhibits the mean January-February position of the Icelandic Low as derived from monthly mean 1000 millibar pressure charts (archived at Environment Canada's Ice Centre). The average position of the Icelandic Low during the winter is southwest of Iceland in the vicinity of 60°N , $30-40^{\circ}\text{W}$. The positions exhibited in Figure 5.4 may be classified as being north or south of the usual location of the Low. Table 5.4 lists the classifications of these positions by year.

The values for ice area and extent from Table 4.1 can be classified in a similar manner, according to above mean conditions, below mean conditions and approximating mean conditions. Mean conditions are defined as ice extent and area values occurring within one standard error (SE) of the 1973-1985 mean. The classifications by year are

FIGURE 5.4

Mean January-February Position of the Icelandic Low (1973-1985)

TABLE 5.4

Classifications of Icelandic Low Positions and Eastern Canadian
Seaboard Maximum Ice Extents (1973-1985)

Icelandic Low Positions (1973-1985)

Eastern
Canadian
Seaboard
Ice Extents
(1973-1985)

	South	Average	North
Below Mean	1978 1980	1982	1979 1981
Mean	1977 1985		
Above Mean		1974 1975	1973 1983 1976 1984

listed in Table 5.4.

The cross-classification format of Table 5.4 facilitates the comparison of the Icelandic Low positions and the ice areas and extents. The years 1978 and 1980, with below mean ice extent, correspond to southern positions of the Icelandic Low. The years 1973, 1976, 1983 and 1984, with above normal ice conditions correspond to northern positions of the Icelandic Low. These years therefore are consistent with the findings of Johnson (1980) and Rogers (1985). The years 1974 and 1975, which are classified as having above mean ice extents, correspond to normal positions of the Icelandic Low. The Low is also in a normal position during 1982, which is classified as having a below mean ice extent. Since these years do not follow the expected results, some other factor must have affected the ice growth to produce anomalies in extent. The years 1985 and 1977 had ice extents close to the mean of the 13-year period, but the positions of the Low were south of the normal position. In fact, these two years had the most southerly positions of all the years. Therefore, the extreme southerly positions had little influence on ice extents along the Eastern Canadian Seaboard. The years 1979 and 1981 have ice extents and Low positions opposite to what is expected. Both years have below mean ice extents corresponding with northerly positions of the Icelandic Low.

To summarize, 6 years out of the 13-year study period had ice extents and Icelandic Low positions that are consistent with the findings of Johnson (1980) and Rogers (1985). This represents only half of the time period. Therefore the relationship between ice extent and

the winter Icelandic Low position is not consistent for the Eastern Canadian Seaboard.

5.2.4 Winds

During the winter months, with the influence of a normal position of the Icelandic Low, the prevailing wind direction along the Eastern Canadian Seaboard is from the west to northwest direction. A westerly wind brings cold air from the Canadian interior and will move the ice offshore, thus increasing ice extent. It follows therefore that above normal wind speeds would result in above normal ice extent. Symonds (1984) indicates that increased wind speed results in conditions more conducive to ice formation by increasing the air-sea heat flux. For these reasons, prevailing wind direction and speed data for the 1973 to 1985 time period were compared to the ice area and extent trends.

Table 5.5 lists the February (1973-1985) prevailing winds for a selection of meteorological stations along the Eastern Canadian Seaboard. The data were extracted from Environment Canada Monthly Record publications archived at the Ice Centre in Ottawa. Except for a few cases, the westerly wind is listed as the prevailing wind for all stations. In 1981, which experienced the smallest maximum ice extent, Grindstone Island and Battle Harbour reported a prevailing south wind, which is generally known to be warm. The remainder of the stations, though, reported the usual westerly direction. Examination of the wind speeds does not yield any specific pattern. Maximum and minimum speeds occur in different years for all the stations. The year 1982 has three

TABLE 5.5

February Prevailing Wind Directions and Speeds (km/hr) (1973-1985)

Station	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Grindstone I.	W 36.7	W 38.7	NW 29.8	NW 36.2	NW 28.7	W 28.2	WNW 41.5	NW 28.0	S 32.5	WNW 42.4	n/a	n/a	WNW 18.5
Eddy Point	WNW 21.1	NW 22.0	NW 17.4	WNW 19.5	NW 18.8	WNW 16.9	WNW 19.8	NW 18.4	NW 18.2	WNW 21.7	WNW 20.9	NW 16.4	WNW 14.8
St. John's	WSW 25.9	W 32.3	W 28.5	W 31.9	W 26.7	W 30.1	W 26.5	W 27.8	W 21.5	W 34.6	N 25.6	WSW 27.3	W 24.1
Bonavista	SW 28.8	WSW 38.8	WSW 30.7	W 34.6	NW 36.2	WNW 40.5	W 37.0	W 34.9	W 29.5	W 42.4	WNW 36.6	SW 37.3	WNW 29.6
Battle Harbour	NW 31.2	WSW 33.6	NW 21.9	WNW 29.8	WNW 31.8	WNW 34.7	WNW 34.4	W 35.1	S 30.9	W 35.1	WNW 30.4	n/a	NW 29.6
Hopedale	W 22.2	NW 21.4	WSW 17.1	WSW 23.7	WNW 23.4	WNW 28.8	W 30.0	NW 28.4	n/a	W 24.4	SSW 18.7	WNW 23.7	n/a
Cape Dyer	E 9.8	WNW 16.6	NW 15.6	n/a	WNW 16.0	E 12.5	WNW 23.8	WNW 15.1	WNW 10.1	WNW 11.1	WNW 8.8	ENE 2.6	NW 13.0

Source: Data archived at Environment Canada's Ice Centre in Ottawa.

stations reporting high winds, but this does not correspond to above average maximum ice conditions.

The prevailing wind data collected therefore does not, on its own, explain the interannual variability in ice extent. Saulesleja and Phillips (1982) examined monthly geostrophic wind speeds for a station in the Labrador Sea and concluded that winds in the 1970's were stronger than in the 1960's. These higher than usual winds speeds agree with the higher than normal ice extent observed in the early 1970's.

5.3 Oceanographic Parameters

5.3.1 Sea Surface Temperature

Sea surface temperature exerts a control over maximum ice extent in that colder water temperatures are more conducive to ice growth. Thus it follows that above normal water temperatures would correspond to below normal ice extent and vice versa (Symonds, 1984). In accounting for the ice extent variation seen in the passive microwave data, it is therefore necessary to examine sea surface temperature trends for 1973 to 1985.

Oceanographic conditions for the Northwest Atlantic covering the 1970-1979 decade have been examined by Stein (1982) and Trites (1982). Trites (1983) and Trites (1984) extend the analysis to include the years 1980 to 1983. These investigations therefore cover almost completely the time period of interest.

Trites (1982) presents a review of interannual variability in sea surface temperature for several regions along the Eastern Canadian

Seaboard, including the Labrador Shelf and Sea, the Grand Banks and the Gulf of St. Lawrence. These regions lie within the Northwest Atlantic Fisheries Organization (NAFO) convention area, as does the entire Eastern Canadian Seaboard as illustrated in Figure 5.5. Sea surface temperature anomalies are also analysed for $1^{\circ} \times 1^{\circ}$ grid squares for geographic areas within NAFO subareas 2, 3 and 4. For the 1970-79 decade, Trites reports a cooling trend occurring from 1970 to 1975, with surface temperatures returning to normal by 1978.

Stein (1982) examines autumn sea surface temperature anomalies for the Labrador Current, covering the years 1969 to 1980. For his analysis the Labrador Current is divided into two components - the polar component along the continental shelf, and the Irminger Current (warm component) which is seaward of the shelf. Stein concludes that during the early 1970's negative temperature anomalies were evident, mainly in the Irminger part of the Labrador Current. From 1974 to 1978 a general increase in temperature is evident, corresponding with warming of the polar component of the current. A declining trend is reported in 1979 and 1980 for the Irminger component, while 1980 saw increasing temperatures for the polar component. Stein therefore agrees with Trites (1982) on the cooling trend in the first half of the decade, followed by the warming trend.

Trites (1983) presents a table of sea surface temperature anomalies for the 1972 to 1982 time period for East Coast water masses. Regions corresponding to the Eastern Canadian Seaboard study area are extracted

FIGURE 5.5

The NAFO Convention Area

and listed in Table 5.6. A mean anomaly value is calculated for all the regions for each year, and the resulting trend is presented graphically in Figure 5.6. Since the SST anomalies correspond to regions south of 50°N, there may be limited correlation with ice extent over the Eastern Seaboard as a whole. Data from the regions north of 50°N would be necessary. By comparing visually the curves in Figure 5.6 some (qualitative) observations can be made. The year 1981, which exhibits the lowest ice area and extent values, also shows the largest positive SST anomaly. The SST curve does portray a negative to positive SST anomaly trend from 1973 to 1979, which matches the decreasing trends exhibited in ice extent and area over the same time period. Correlation coefficients were calculated for the curves and are listed below:

SST Anomalies vs. Ice Area = -0.7917 (n = 10)

SST Anomalies vs. Ice Extent = -0.7813 (n = 10)

Both r-values were tested and found to be statistically significant at the 99.5% confidence level. The SST anomalies are negatively associated with the ice area and extent values, as expected. Negative SST anomalies correspond to increases in ice area and extent, while positive SST anomalies correspond to decreases.

Trites (1984) presents sea surface temperature anomalies from 1972 to 1983 for subareas corresponding to the Labrador Offshore, the East Newfoundland Waters and the Gulf of St. Lawrence. Figure 5.7 outlines his results with these areas highlighted. Observed in this figure is a period of negative SST anomalies from 1972 to 1975 over most of the region. The years 1977 to 1983 are characterized by above normal SST's.

TABLE 5.6

Sea Surface Temperature Anomalies ($^{\circ}\text{C}$) for the Eastern Canadian Seaboard (1973-1982)

<u>Region</u>	<u>1973</u>	<u>1974</u>	<u>1975</u>	<u>1976</u>	<u>1977</u>	<u>1978</u>	<u>1979</u>	<u>1980</u>	<u>1981</u>	<u>1982</u>
East Nfld.	-0.07	-0.38	-0.12	-0.16	0.12	0.19	0.68	0.01	0.82	0.24
	-0.25	-0.57	-0.30	0.22	-0.11	0.27	0.61	0.20	0.96	0.40
	-0.11	-0.33	-0.63	0.34	0.16	0.31	0.30	-0.08	1.19	0.19
Gulf	-0.00	-0.38	-0.22	0.11	0.10	0.25	0.48	0.22	0.49	0.41
	-0.28	-0.39	-0.43	0.27	0.03	0.35	0.49	0.03	0.66	0.26
Mean	-0.14	-0.41	-0.34	0.16	0.06	0.27	0.51	0.08	0.82	0.30

Source: ^ATrites (1983)

FIGURE 5.6

Trends in Ice Area and Extent Compared to East Coast Sea Surface Temperature Anomalies (1973-1982)

FIGURE 5.7
Annual Sea Surface Temperature Anomalies for the Eastern Canadian
Seaboard (1972-1983)

Adapted from: Trites (1984)

The results of these sea surface temperature investigations (Trites, 1982; Stein, 1982; Trites, 1983; Trites, 1984) compare favourably with the ice extent and area trends for the Eastern Canadian Seaboard. Generally, years with colder than normal SST's correspond to above normal ice extent, and vice versa, as expected. The largest positive anomaly (Trites, 1983) does in fact correspond to the year of least maximum ice extent and area for the 1973 to 1985 time period.

5.4 Significance of the Climatological and Oceanographic Comparisons

The objective of the climatological and oceanographic comparisons has been to account for the interannual variability observed in the ice extent and area values for the Eastern Canadian Seaboard. The seasonal air temperature and accumulated freezing degree day values showed the highest statistical correlations with the ice extent and area trends. Since the air temperature and freezing degree day parameters are both indications of the severity of a winter, the high correlations are to be expected. Markham (1976) indicates that variation in ice cover can be inferred from winter air temperature records, since air temperature is closely related to the degree of ice formation. The results of the seasonal air temperature and FDD comparisons are evidence of this relationship. The degree of association between the two variables was determined by performing a bivariate correlation. The resulting r-value of -0.8550 ($n = 13$) was statistically significant at the highest confidence level of 99.9%. Therefore the seasonal air temperature and FDD accumulation variables are reasonably associated. As expected, the rela-

tionship is such that decreases in temperature correspond to increases in FDD accumulations.

The sea surface temperature comparison also exhibited favourable results in terms of explaining ice extent variation. The results support the relationship that abnormally cold water is associated with above normal ice extent, and above normal temperatures with below normal ice extent (Dunbar, 1982; Symonds, 1984). Trites (1984) indicates that sea surface temperature anomalies are closely linked with air temperature patterns. As a result, it is not surprising that the air temperature and water temperature comparisons to ice extent both yield positive results. A correlation coefficient of 0.6561 ($n = 10$) was calculated for the two variables, and a test of the value indicated statistical significance at the 97.5% confidence level. This confirms the close association between air temperature and sea surface temperature.

The results of the position of the Icelandic Low comparison with ice extent are not straightforward. Only 6 out of the 13 years exhibit ice extent and Low positions which correspond to the results of previous studies. Thus, it is not possible to conclude that the variation in the Icelandic Low winter position accounts for the interannual variability in ice extent from 1973 to 1985. The Icelandic Low controls the winter air circulation along the Eastern Canadian Seaboard, therefore affecting wind and temperature characteristics. It is the air temperature pattern which shows a more direct pattern correlation with ice extent. The position of the Icelandic Low will also tend to steer storms through the area, as discussed by Crane (1978), and therefore could be an area for

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

future research.

The February prevailing wind data did not show any significant relationship with the variation in ice extent. Symonds (1984) indicates that a combination of increased wind speed and cold temperature creates conditions more conducive to ice formation. Although temperature and wind are somewhat interdependent, Markham (1976) points out that westerly winds may be cold or mild depending on their upwind source. Therefore higher westerly wind speeds may not necessarily correspond with the colder temperatures which would result in increased ice formation. Thus the relationship between westerly wind speed and ice extent is not a direct one.

From these comparisons, it seems that air temperature (seasonal and accumulated freezing degree days) and water temperature variation patterns exhibit the clearest and most unambiguous relationship with the ice extent and area interannual variability. The Icelandic Low position is known to exert a controlling influence over the ice season (Markham, 1976), but a close relationship with ice extent has not been observed in this analysis. The climatological and oceanographic parameters examined are interrelated in one way or another, through atmosphere-ocean interaction processes. Therefore it is not possible to define one controlling mechanism of maximum ice extent along the Eastern Canadian Seaboard. It can only be concluded, that during the 1973 to 1985 time period, years of extreme maximum ice extent corresponded to extremes in winter seasonal air temperature values and accumulations of freezing degree

days, and positive and negative sea surface temperature anomalies.

5.5 Regional Maximum Ice Extent Analysis

In examining the Eastern Canadian Seaboard as a whole, trends in maximum ice extent in the individual subregions may be masked. The maximum extent does not necessarily occur at the same time in all regions, nor does it usually correspond to the maximum extent for the Eastern Canadian Seaboard as a whole. For example, in February 1985 the pack ice was so extensive in the East Newfoundland waters that five drilling rigs had to be moved off location and drilling operations were suspended for many weeks (Eastern Offshore News, 1985). The Eastern Canadian Seaboard maximum ice area and extent values for 1985 are not abnormally high. Therefore the extensive conditions of the East Newfoundland waters are hidden by the contributions of the other subregions, where conditions were normal. Since offshore operations tend to cluster in specific regions of the Eastern Seaboard, it is of interest to examine the maximum ice extent trends for its four main subregions, namely Davis Strait, Labrador Sea, East Newfoundland Waters, and the Gulf of St. Lawrence. The boundaries of these subregions are defined in Figure 3.1.

The maximum ice extent and area values for the individual subregions are derived according to the methodology described in Chapter 4 (Section 4.4.3.1). For this analysis SMMR data is used, covering the years 1979 to 1985, because of the ease and consistency of computer generation of statistics. Figure 5.8 graphically displays the maximum

FIGURE 5.8

Eastern Canadian Seaboard Regional Trends in Maximum Ice Extent
and Ice Area (1979-1985)

ice area and extent values for the defined subregions, producing curves of trends over time. Table 5.7 lists the specific values, with maxima and minima for the 1979-1985 period highlighted. By examining the trends produced, one can see how individual regions vary as compared to one another.

An initial examination of the curves in Figure 5.8 reveals that the Davis Strait and Labrador Sea regions exhibit similar patterns in maximum ice extent. The East Newfoundland Waters and the Gulf of St. Lawrence regions also exhibit similar trends. Maximum extent for the 1979 to 1985 period occurs in Davis Strait and Labrador Sea in 1983, while the East Newfoundland Waters and Gulf show maximums in 1985. Therefore, the two southern regions exhibit maximum conditions approximately 2 years after the northern regions. Minimum conditions persist in all regions from 1979 to 1981, which corresponds to minimum conditions seen in the Eastern Canadian Seaboard trends. The increasing trend starts in Davis Strait after 1981, in the Labrador Sea after 1982, in the East Newfoundland Waters after 1982, and in the Gulf of St. Lawrence after 1983. Thus there appears to be a delayed reaction as one progresses southwards along the Eastern Seaboard.

The trends (1979-1985) observed in the individual regions suggest possible areas of future research. The similarities in trends between the Davis Strait and Labrador regions and the East Newfoundland and Gulf regions may be due to similarities in ocean current patterns, and thus warrants further research. The time lag present in the maximum ice extent from north to south indicates that it may be possible to predict

TABLE 5.7

Maximum Ice Extent and Area Values (km^2) for the Eastern Canadian
Seaboard Regions (1979-1985)

		1979	1980	1981	1982	1983	1984	1985
Gulf	IA	115253	94191	74812	88387	54558 *	90861	119524
		25/02	3/03	16/02	17/03	14/03	15/02	1/03
	IE	162580 •	149516	135000	149516	104516 *	130645	156774
		25/02	3/03	22/02	17/03	14/03	15/02	1/03
E. Nfld. Waters		73572	70544	48476 *	52211	92578	145418	199004 •
		9/03	9/03	22/02	17/03	14/03	21/02	13/03
		149516	126290	90000 *	98709	145161 •	233709	316451 •
		9/03	9/03	22/02	17/03	26/03	27/02	7/03
Labrador		147329	144910 *	148678	154911	285383 •	265864	156842
		9/03	9/03	16/02	17/03	26/03	15/02	1/03
		251129	223548 *	254032	229354	397741 •	389031	242419
		3/03	9/03	28/02	17/03	26/03	15/02	19/03
Davis Strait		321107	311137	295343 *	443811	530319 •	516386	373045
		9/03	9/03	22/02	23/03	20/03	15/02	13/03
		428225	406451	399193 *	560321	634354 •	608225	486289
		9/03	22/03	22/02	17/03	20/03	15/02	13/03

• Maximum (1979-1985)

* Minimum (1979-1985)

IE = Total spatial extent of ice

IA = Total area of ice (IE minus amount of open water)

above normal maximum ice extent, by monitoring northern conditions. In order to derive any significant relationship, a much larger data set would need to be examined, longer than the available passive microwave data set. The patterns indicated in the analysed portion of the passive microwave data set do warrant further research, on the way to achieving the ability to predict extreme maximum ice extent in regions of heavy offshore activity, i.e., the East Newfoundland Waters.

5.6 Climatic Significance of Maximum Ice Extent Trends

The 13-year archive of passive microwave data is considered brief in terms of climatic studies. Investigations of climatic change require many decades of data in order to derive significant trends. If the passive microwave ice information is combined with historical ice information, such as Atmospheric Environment Service ice charts, general trends can be derived. The main drawback of using historical data is the inconsistency of information coverage. Many remote regions are not monitored on a continuous basis due to the high costs of aircraft reconnaissance. Therefore the amount of ice information available is limited.

Markham (1980) presents median, maximum and minimum ice extents from AES ice charts for the 1963 to 1973 decade covering the Eastern Canadian Seaboard. The combination of this information with the passive microwave ice information extends the available data set to 22 years. Thus there is the potential to derive more significant climatic trends. Unfortunately there are drawbacks to using the Markham (1980)

information. The ice extent information is limited to the East Coast region south of 55°N , which only represents half of the defined Eastern Canadian Seaboard. The ice extents represent maximum, median, and minimum extents for the entire 1963-1973 decade, and thus interannual variation cannot be observed. Despite these drawbacks, the information from Markham (1980) can be combined with the passive microwave ice extent information to derive general trends which would be of climatic interest.

Figure 5.9 exhibits the median ice edge for the end of February (1963-1973) from Markham (1980) as compared to the median ice edge derived from the 1973-1985 passive microwave maximum ice extents. Along the East Newfoundland coast the extents are similar in shape, although the 1973-1985 median extent is displaced further south than the 1963-1973 median. In the Gulf of St. Lawrence the 1963-1973 median is of greater extent than the 1973-1985. Overall, the difference between the two medians is very small and thus an increasing or decreasing trend in ice extent can not be readily established. The same approach can be applied in other ice regions using historical information; possibly yielding more significant climatic results. Despite the limitations of historical ice information, there is the potential of combining it with passive microwave ice information in order to investigate climatic change.

FIGURE 5.9

Median Maximum Ice Extents from AES Ice Charts (1963-1973) and
Passive Microwave Data (1973-1985)

Adapted from: Markham (1980)

CHAPTER 6

CONCLUDING REMARKS

6.1 Summary of the Interannual Variability Analysis

Maximum ice extent along the Eastern Canadian Seaboard is a parameter of much interannual variability. The analysis of maximum ice extent and area trends derived from passive microwave satellite data yields significant results towards a better understanding of ice conditions in the Eastern offshore regions. Although one definite controlling mechanism of maximum extent was not identified, the correlations of maximum ice extent and area trends to trends in seasonal air temperature, accumulated freezing degree days, and sea surface temperature are significant. Thus, the objective of accounting for the observed maximum ice extent interannual variability from 1973 to 1985 is achieved. The rôle of atmospheric circulation bears further research, especially in light of the need for a greater understanding of the atmosphere-ice-ocean interaction.

The passive microwave satellite data set available is an important source of information on global, hemispheric and regional ice conditions. The consistency and complete global coverage of the data set ensures an excellent source of information concerning ice conditions in remote regions. The methodology applied to the Eastern Canadian

Seaboard can be applied to any other ice region, as large as the whole Arctic or as small as the Gulf of St. Lawrence. Interannual variability in ice conditions can be studied both quantitatively and qualitatively with the available data set. Even though the resolution of the data is coarse (30 km), the data set offers many advantages over traditional ice charts based on aerial reconnaissance, such as those produced by the Atmospheric Environment Service. Ice charts are generally produced on a regional basis and limited to certain times of the year. For example, north of 55°N ice information is generally not available during the winter months at the time of maximum ice extent. Passive microwave satellite data is available continuously for all regions of interest.

6.2 Limitations of Methods and Data

The climatological and oceanographic data available for the Eastern Canadian Seaboard is limited to coastal meteorological stations and oceanographic stations. The spatial distribution of these stations is not consistent over the area, which creates problems in deriving representative means for the study area as a whole. Ideally, the resolution of the climatological and oceanographic data should equal that of the collected microwave data to form a representative picture of conditions over the whole area. Despite this limitation, the climatological and oceanographic data used in the comparisons of Chapter 5 yielded reliable results. For the purposes of this research, the data used was therefore sufficient.

The resolution of the passive microwave data is limited to 30 km,

which is considered coarse in terms of satellite data. For analysis of ice conditions on a large regional basis, such as the Eastern Canadian Seaboard, the resolution is not a limitation. As indicated previously, ice edge positions can be determined to an accuracy of ± 15 km. For studying ice extent variation on an annual basis, this accuracy is sufficient.

6.3 Implications for the Canadian Offshore Scenario

Wintertime offshore activity along the Eastern Canadian Seaboard is dependent upon the severity of ice conditions. The optimal goal in sea ice research would be to achieve the ability to predict extremes in ice extent, in order to plan offshore activities accordingly. Wadhams and Lever (1985) indicate that improved forecasting of ice extent and concentration would improve the efficiency of all types of marine operations, especially in offshore Newfoundland and Labrador. The results of the interannual variability analysis provide a significant contribution to the understanding of maximum ice extent within the regions of interest. The trends observed in the individual subregions suggest that the time-lag in the ice extent relationship between northern and southern regions is an area needing future research, on the way to achieving the ability to predict extremes in ice extent. The monitoring of seasonal (winter) air temperatures and sea surface temperatures may give insight into the degree of maximum ice extent that will be attained in a winter season. The optimal goal would be to define predictors that could be monitored previous to the ice season, in the fall time period.

6.4 Applications to Climate Research

Climate variability is an important area of research today within the scientific community. The role of sea ice interannual variability as an indicator of climate variability has been emphasized by many scientists (e.g., Maykut, 1978; Crane, 1981; Zwally, 1984). Passive microwave satellite data can be a useful source of ice concentration and extent information needed in climatic research endeavours. Comiso and Zwally (1984) indicate that even though the resolution of the data is limited (~ 30 km), spatial and temporal detail can be derived, and overall conditions of sea ice cover can be statistically analysed. The ice concentrations and ice area values derived from the satellite data can be used as input in various climate models investigating the atmosphere-ice-ocean processes. The satellite platform provides near-global coverage not available with traditional methods of ice reconnaissance. Therefore, for any one region a consistent sea ice data set is available in the passive microwave satellite data base. The digital format of the data allows for a variety of quantitative analyses to be performed using computers. Thus, detailed analyses of climate-sea ice interactions are possible, with comparisons of ice concentration and extent statistics to computer-based digital climate data sets. The climatological and oceanographic comparisons detailed in Chapter 5 represent simple examples of the analyses possible with the data set.

6.5 The Future of Passive Microwave Satellite Remote Sensing

At the time of the writing of this thesis, the Nimbus-7 SMMR is still operating beyond its predicted life expectancy. In order to ensure continued data collection and thus extend the present passive microwave data set, the U.S. Department of Defense is planning to launch the Special Sensor Microwave Imager (SSM/I) on board its series of DMSP satellites. The SSM/I will provide complete coverage of the polar regions in one day and operate daily (NASA, 1984). With the addition of the 85.5 GHz channel, the spatial resolution of the data will be reduced to approximately 15 km. The SSM/I performance characteristics are outlined in Table 6.1. At this time, the proposed launch date of the SSM/I is between December 1986 and March 1987. When it is launched, the sensor will ensure a passive microwave data set to combine with that of the ESMR and SMMR to cover many decades. The application of this increased data set to future sea ice research will be significant, allowing for more detailed and representative studies of sea ice and climate interaction. This will bring closer the possibility of predicting extreme ice extents along the Eastern Canadian Seaboard.

TABLE 6.1
SSM/I Performance Characteristics

Parameter	Radiometer Performance			
Center Frequency, GHz	19.35 $\pm$ 0.05	22.235 $\pm$ 0.05	37.0 $\pm$ 0.1	85.5 $\pm$ 0.3
Polarization	Vert. & Horz.	Vert.	Vert. & Horz.	Vert. & Horz.
Radiometric Accuracy, K	1.5	1.5	1.5	1.5
ΔT (noise), K	0.8	0.8	0.6	1.1
Dynamic Temp. Range, K	375	375	375	375
Effective Resolution, km (3 dB antenna beamwidth; includes integ. time)	70 $\times$ 45	60 $\times$ 40	38 $\times$ 30	16 $\times$ 14
Integration Time, ms	7.95	7.95	7.95	3.89

Source: NASA (1984)

APPENDIX A.1

Maps Displaying Maximum Ice Extent Conditions (1973-1985)

Dates: February 19, 1973
February 28, 1974
February 25, 1975
February 29, 1976
March 5, 1977
March 9, 1979
March 9, 1980
February 22, 1981
March 17, 1982
March 26, 1983
February 21, 1984
March 7, 1985

Note: These maps are reductions of 1:5,000,000 mylar maps. The reduction process degrades the quality of the map product somewhat, but maximum ice extent is still discernable by locating the 10% or 15% ice concentration contour.

107

111

112

APPENDIX A.2

Ice Area and Extent Statistics (1973-1985)

Nimbus-5 ESMR East Coast Ice Coverage (Sq. km)

Date	15-35%	35-65%	65-85%	85-99%	99-100%	Total Ice Area	Total Ice Extent
19/02/73	28850.75	93628.85	200322.18	518834.45	156048.08	997683.86	1289755.50
26/02/73	27580.59	76209.53	212842.32	458070.05	184354.47	959056.96	1228787.90
21/02/74	44092.65	133185.22	215019.73	422012.06	75483.72	889793.38	1263626.50
28/02/74	27762.04	109959.46	236793.88	437370.09	87822.41	899707.88	1209916.90
7/03/74	38104.76	137902.95	243326.13	388625.03	68951.48	876910.35	1244029.80
14/03/74	37016.06	101249.80	212842.32	351899.30	75483.72	778491.20	1092336.50
18/02/75	31391.07	112136.87	299938.92	449389.42	25403.18	918259.46	1263626.50
25/02/75	32298.32	129193.29	369616.20	390628.25	7983.86	929719.92	1312981.20
4/03/75	33749.93	153144.86	181814.15	363250.89	32661.23	764621.06	1111207.50
11/03/75	33205.58	88185.31	223729.39	515495.74	52983.77	913599.78	1220804.00
21/02/76	22137.05	99435.29	325523.54	418673.36	31935.42	897704.66	1208465.30
29/02/76	31209.62	151330.34	186713.34	478102.27	63870.84	911226.41	1259997.50
8/03/76	31391.07	135725.54	256934.97	397305.66	46451.52	867808.76	1217900.80
25/02/77	27036.24	72217.60	157318.23	247731.76	275080.10	779383.93	1006691.50
5/03/77	24495.92	72580.50	115947.35	182293.18	164068.22	780029.89	1015401.20
14/02/78	2449.59	12520.14	45181.37	706330.21	----	766481.31	845562.83
28/02/78	8346.76	12247.96	20141.09	674449.22	----	715185.03	817982.24
4/04/78	17147.14	45453.54	58245.85	626940.20	----	747786.73	950078.75

EAST COAST ICE COVERAGE (SQ. KM.)
 43 TO 70 DEG. N. 170 TO 140 DEG. W.
 PH.D.S. ASSOCIATES INC.

DATE (YY/MM/DD)	TOTAL ICE (0-15)	TOTAL ICE (15-35)	TOTAL ICE (35-65)	TOTAL ICE (65-95)	TOTAL ICE (95-99)	TOTAL ICE (99-100)	TOTAL ICE (15-100)	TOTAL EXTENT (15-100)
79050	14761	45629	86048	223465	147062	8662	513664	834676
79056	11496	32805	86551	268068	186965	0	572188	849192
79062	22058	33577	87043	268315	217523	5770	608557	902981
79068	8960	14559	166618	197224	221955	0	620307	958063
80063	17444	14586	111412	175632	235005	0	557586	854998
80065	13883	26221	124971	233156	222511	0	602259	898547
80067	8103	32999	139210	189432	179517	0	541158	850643
81047	9824	24820	135637	218449	155122	0	530636	833224
81053	9006	25153	171204	208868	156804	0	558026	868063
81059	6013	33837	153486	138015	185182	0	510520	830321
82058	13097	34636	121582	225942	286179	0	669783	997254
82076	7163	26942	142909	225180	310406	1445	725331	1037901
82082	10888	29686	123682	143318	391522	2893	710151	994253
82667	8806	23188	59655	243719	510042	1439	878243	1167094
83073	8871	23628	104941	16543	593521	4324	904958	1181611
83079	12844	34194	95218	185634	562439	1452	915244	1252739
83083	7814	30230	138087	224638	509303	0	1003933	1299320
84046	8848	19025	124639	333800	526468	0	915244	1329675
84052	6959	24348	112422	307745	559467	0	1000982	1335481
84056	6837	25822	119536	224969	560714	0	971040	1299191
84064	5625	23009	127376	229344	494184	1446	875657	1178707
85060	5644	29397	95236	271188	394187	1504	605893	1103224
85066	10554	45614	120951	311826	314925	1452	794828	1188869
85072	8445	31520	123134	318112	340325	1452	814942	1143869
85078	7883	36202	138060	272503	304005	8690	759459	1110482

APPENDIX A.3

Air Temperature and FDD Data for Meteorological Stations
Along the Eastern Canadian Seaboard

Eastern Canadian Seaboard February Mean Air Temperatures in °C (1973-1985)

Station	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Grindstone I.	-7.8	-8.3	-11.2	-7.6	-7.9	-7.4	-8.7	-8.0	-3.5	-8.5	n/a	n/a	-7
Eddy Point	-5.7	-6.8	-8.4	-4.1	-5.0	-6.6	-8.6	-6.7	-1.8	-6.7	-3.9	-1.8	-6
St. John's	-1.6	-4.4	-10.5	-5.0	-6.2	-3.8	-7.1	-4.9	-2.8	-7.1	-4.2	-1.9	-6
Bonavista	-3.9	-6.0	-10.8	-6.1	-6.0	-2.9	-6.9	-4.8	-2.5	-7.0	-5.3	-3.0	-6
St. Anthony	-10.9	-10.5	-15.1	-12.8	-9.1	-5.6	-11.8	-10.3	-5.6	-15.5	-10.2	-9.3	n/a
Battle Harbour	-12.1	-10.3	-15.4	-13.8	-8.4	-4.8	-11.5	-9.5	-6.0	-15.6	-11.7	n/a	-13
Hopedale	-19.3	-14.4	-18.1	-19.4	-15.4	-10.9	-16.0	-13.7	-9.5	-20.1	-19.6	-17.7	n/a
Cape Dyer	-27.9	-20.4	-23.9	-26.8	-22.5	-20.5	-26.7	-19.4	-26.9	-27.5	-30.0	-35.2	-23
Broughton I.	-28.6	-23.7	-24.9	n/a	-27.0	-21.7	-31.2	-21.1	-26.6	-26.9	-29.9	n/a	-25
Cape Hooper	-31.4	-25.5	-25.4	n/a	-25.8	-22.4	-32.5	-21.1	-26.6	-27.4	-30.8	n/a	-41
Mean	-14.9	-13.1	-16.4	-12.0	-13.0	-10.7	-16.1	-12.0	-11.2	-16.2	-9.3	-11.5	-15.9

Eastern Canadian Seaboard March Mean Air Temperatures in °C (1973-1985)

Station	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Grindstone I.	-3.6	-4.7	-4.3	-5.3	-2.3	-5.0	-2.1	-4.3	-1.1	-5.1	n/a	n/a	-5
Eddy Point	-1.4	-2.9	-2.5	-2.2	-0.5	-3.3	0.3	-2.8	0.3	-3.0	-0.8	-2.5	-3
St. John's	-2.3	-3.6	-1.6	-3.3	-2.2	-3.6	0.7	-2.1	-0.7	-4.0	-1.2	-1.6	-5
Bonavista	-3.9	-4.3	-2.2	-4.1	-2.3	-3.5	0.6	-2.5	-0.8	-3.7	-1.6	-2.0	-5
St. Anthony	-6.8	-9.0	-5.3	-9.6	-4.2	-9.4	-3.5	-5.6	-2.6	-9.2	-4.6	-7.6	n/a
Battle Harbour	-7.3	-9.4	-5.5	-10.3	-4.0	-9.9	-4.2	-5.7	-2.5	-9.2	-6.5	n/a	n/a
Hopedale	-11.2	-15.1	-11.4	-15.4	-7.2	-15.9	-11.1	-9.5	-6.0	-13.8	-13.1	-12.2	n/a
Cape Dyer	-23.6	-22.9	-25.6	-23.2	-18.4	-26.0	-21.3	-19.8	-17.3	-24.2	-26.6	-24.7	-22
Broughton I.	-23.3	-26.4	-26.5	n/a	-19.3	-27.1	-21.8	-19.3	-17.6	-25.4	-25.2	-26.4	-25
Cape Hooper	-26.2	-25.7	-27.2	n/a	-21.9	-27.7	-23.4	-20.8	-19.2	-26.1	-26.0	n/a	n/a
Mean	-11.0	-12.3	-11.2	-9.2	-8.2	-13.1	-8.6	-9.2	-6.8	-12.4	-11.7	-11.0	-10.8

Eastern Canadian Seaboard Seasonal (Dec.-Feb.) Mean Air Temperatures in °C (1973-1985)

Station	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Grindstone I.	-7.2	-5.9	-6.4	-5.9	-7.0	-5.1	-5.6	-5.3	-5.4	-5.2	-4.0	n/a	n/a
Sydney	-5.6	-4.9	-5.9	-4.4	-5.6	-4.2	-4.9	-4.7	-4.6	-4.4	-2.8	-3.5	-5.3
St. John's	-5.0	-4.2	-5.9	-3.1	-4.3	-3.1	-3.6	-4.0	-2.5	-3.6	-2.4	-3.0	-4.4
St. Anthony	-9.8	-10.3	-11.4	-9.9	-8.6	-7.2	-8.7	-8.9	-7.0	-9.1	-9.8	-10.4	-9.6
Battle Harbour	-14.3	-13.8	-13.1	-10.9	-8.4	-7.3	-8.7	-8.9	-7.7	-9.4	-11.8	n/a	-11.0
Hopedale	-19.6	-14.6	-16.9	-16.7	-13.3	-13.6	-13.2	-12.4	-12.4	-13.9	-18.6	-17.8	n/a
Cape Dyer	-24.2	-20.9	-26.5	-24.8	-18.6	-23.3	-18.9	-18.9	-23.8	-21.4	-29.4	-30.2	-21.5
Cape Hooper	-28.4	-24.2	-26.7	-24.9	-21.0	-24.2	-22.8	-21.1	-23.7	-25.7	-29.3	n/a	n/a
Mean	-14.3	-12.4	-14.1	-12.6	-10.9	-11.0	-10.8	-10.5	-10.9	-11.6	-13.5	-13.0	-10.4

FUO Accumulations (to the end of February) for the Eastern Canadian Seaboard (1973-1985)

Station	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Grindstone I.	626	540	541	541	632	458	533	464	512	471	393	469	501
Sydney	495	472	520	424	527	395	466	414	469	440	288	354	499
St. John's	454	400	560	295	397	305	282	362	373	258	344	275	401
Battle Harbour	1351	977	1098	1016	807	706	889	841	706	810	1145	1196	1013
Hopedale	1905	1363	1653	1601	1330	1316	1413	1206	1214	1268	1804	1721	1490
Cape Dyer	3109	2358	3175	3042	2363	2750	2599	2436	2791	2595	3430	3492	2606
Cape Hooper	3559	2699	3134	3007	2733	2887	3091	2701	2734	2610	3401	3456	2872

APPENDIX A.4

Accessibility of Nimbus-5 ESMR and Nimbus-7 SMMR Data

A Canadian archive of Nimbus-5 ESMR and Nimbus-7 SMMR data, including the data used for this thesis, exists at the offices of Dr. R.O. Ramseier, Senior Scientist, Ice Research and Development, of the Atmospheric Environment Service. The computer tapes can be accessed by contacting Dr. Ramseier and providing the date (day/month/year) of the tape of interest. The address to which inquiries should be directed is:

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