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Sea Ice Characteristics of the Parry Channel

by

Robert William Gorman, B.A.

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

Department of Geography

Carleton University
Ottawa, Ontario

March, 1988

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Abstract

In this thesis, the ice regimes of the Parry Channel have been defined. Ice characteristics of the Channel were determined from NOAA satellite imagery, A.E.S. ice charts and synthetic aperture radar imagery. Recorded ice behaviour patterns and data on the oceanographic and atmospheric environment were compared to aid in the delineation of the ice regimes and sub-regimes of the Parry Channel. Speculations on the causes of these ice regimes were also made.

Two ice regimes in the Parry Channel have been identified: the eastern Parry Channel ice regime comprising the waterways to the east of central Barrow Strait, and the western Parry Channel which is comprised of the waterways to the west. It is speculated that the marked difference in the sea ice characteristics between these two ice regimes is likely the result of the domination of the eastern Parry Channel by waters of Atlantic Ocean influence and the corresponding domination of the western Parry Channel by waters of Arctic Ocean influence.

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Glossary of Terms

A.E.S.: Atmospheric Environment Service.

Air mass: Volume of atmosphere with characteristic temperature and humidity.

Amphidromic Basin: The counter-clockwise flow of a tidal wave in an enclosed basin caused by Coriolis Forces.

APT: Automatic Picture Transmission.

AVHRR: Advanced Very High Resolution Radiometer.

Big Floe: Sea ice floe 500 - 2000 m across.

cA: Continental Arctic air mass.

Compact: State where the ice concentration is 10/10 and no water is visible but the floes are not frozen together.

Consolidated: State where ice concentration is 10/10 and the floes are frozen together.

Convergence: Sea ice under the influence of converging motion which increases ice stress and pressure.

Coriolis Force: The deflection of a moving object to the right in the northern hemisphere as a result of the rotation of the earth.

Divergence: Sea ice under the influence of dispersive motion that reduces ice stress and pressure.

Ebb Tide: The low water level of the tide.

First Year Ice: Sea ice of not more than one winter growth.

Flaw lead: A lead between consolidated and unconsolidated ice sufficiently wide as to allow navigation by surface vessels.

Floe: Piece of sea ice 20m or more across.

Flood Tide: The high water level of the tide.

Fracture: Process whereby a consolidated ice sheet yields by breaking to external forces.

Freezing Degree Day (FDD): Once unit for 1.0 °C below 0 °C for each day.

Geostrophic: Movement where the pressure gradient force is balanced by the Coriolis Force and gravity.

Giant Floe: Sea ice floe over 10 km across.

Grey ice: Young sea ice of 10-15 cm thickness.

Grey-white Ice: Young sea ice of 15 - 30 cm thickness.

HF: High Frequency.

HRPT: High Resolution Picture Transmission.

Ice Bridge: Boundary between consolidated and unconsolidated ice.

Ice Dam: The compaction of ice floes in a constricting passage such that no further movement of ice in the flow direction occurs.

Ice Edge: The separation between sea ice and open water or ice of differing ages or concentration.

Ice Plug: The jamming of sea ice floes in a waterway that prevent further movement in the direction of flow.

Ice Regime: A water body of defined geographic area that has a unique system of sea ice growth and movement that is distinctive from other surrounding regions.

Ice Sub-regime: An area within an ice regime that has one or two unique ice characteristics separate from other surrounding sub-regimes.

ITOS: Improved TIROS operational satellite.

Lead: A linear opening in ice sufficiently wide as to allow for surface vessel navigation.

mA: Maritime Arctic air mass.

Medium First Year Ice: First year ice of 70 - 120 cm thickness.

Medium Floe: Sea ice floe 100 - 500 m across.

Melting Degree Day (MDD): One unit for 1.0 °C above 0 °C for each day.

MSS: Multi Spectral Scanner.

Multi-Year Ice: Old ice that has survived at least two summers melt.

Neap Tide: Sun or moons high water tide corresponding to the others low water.
Occurs fortnightly at the quarter phases of the moon.

NESS: National Earth Satellite Service.

New Ice: Recently formed sea ice on the sea surface with little definable thickness.

Nilas: Young sea ice up to 10 cm in thickness.

NOAA: National Oceanographic and Atmospheric Administration.

Old Ice: Sea ice that has survived at least one summer melt.

Open Water: Ocean surface free of sea ice.

Polynya: A non-linear shaped opening enclosed in ice.

Pycnocline: A steep vertical gradient of density within a volume of ocean water.

Often used to define distinct layers within an ocean.

RBV: Return Beam Vidicon.

SAR: Synthetic Aperture Radar.

Second Year Ice: Sea ice that has survived only one summer melt.

Shear Zone: A boundary between a highly mobile ice cover and a consolidated or stagnant ice cover.

SLAR: Side Looking Airborne Radar (Real Aperture).

Small Floe: Sea ice floe 20 - 100 m across.

Spring Tide: Sun and moons high water tide correspond. Occurs fortnightly at the full and new moon.

STAR-1: Sea Ice and Terrain Assessment Radar version 1.

STAR-2: Sea Ice and Terrain Assessment Radar version 2.

Tidal Shoaling: Increase in tidal height and stream as the tidal wave propagates into shallow waters.

TIROS: Television Infra-Red Observational Satellite.

Thick First Year Ice: First year ice of over 120 cm thickness.

Thin First Year Ice: First year ice 30 - 70 cm thick.

Vast Floe: Sea ice floe 2 - 10 km across.

VHF: Very High Frequency.

VHRR: Very High Resolution Radiometer.

Water Mass: Volume of ocean with characteristic temperature and dissolved particulate concentration. Often associated with one of the worlds oceans.

WMO: World Meteorological Organization.

Young Ice: All forms of sea ice between 10 - 30 cm in thickness.

‰: Parts per thousand concentration.

Chapter 1

Introduction

1.1 Introduction

The Parry Channel, which includes the waterways of Lancaster Sound, Barrow Strait, Viscount Melville Sound and M'Clure Strait, has long been known as the deep water route of the north-west passage. The Channel is named after Sir William Parry, a Royal Navy officer who, in 1819, first speculated that the waters of Lancaster Sound formed part of the north-west passage (Mowat 1973). However, it was not until the discoveries of Robert M'Clure, in 1851, that the waterways of the Parry Channel were conclusively proven to be the north-west passage (Mowat 1973). Attempts by these early explorers to navigate the Parry Channel were thwarted by heavy sea ice, often with fatal consequences. To this day, the year-round existence of high concentrations of sea ice in the Parry Channel presents a formidable barrier to marine navigation.

The recent discovery and exploitation of large quantities of hydro-carbons and mineral deposits in the high Arctic since the late 1970's has greatly increased commercial shipping within the Parry Channel. The lead-zinc mines of Nanisivik, on northern Baffin Island, and Polaris, on Little Cornwallis Island, as well as the Bent Horn oil production facility on Cameron Island, all rely on marine transportation

through the Parry Channel to export these resources to market. However, due to the sea ice environment these exports have been limited to a period from late July to early October each year.

Much work has been undertaken in the past few years on the development of more capable icebreaking vessels and ice navigation systems using remotely sensed data to extend the navigation season within the Parry Channel. Examples include the icebreaking commercial vessel M.V. Arctic, which has extended the navigation season from late May to early December (Luce et al. 1987). This season extension has been the result of improved icebreaking performance and the development of specialized ice navigation systems utilizing, onboard the vessel, remotely sensed images from aircraft and spacecraft to avoid difficult ice areas. The goal of these initiatives is to develop a system for year-round marine navigation in the Parry Channel. This goal will be further expanded with the commissioning of the Canadian Polar 8 icebreaker in the early 1990's. However, experience with the M.V. Arctic has shown that improved icebreaking performance and remotely sensed data alone onboard the vessel do not extend the navigation season. What is also needed is a thorough understanding of the ice environment the vessel will face. Such an understanding would enhance the prediction of difficult ice conditions such that proper voyage planning, and route selection, may be made. It is the purpose of this thesis to describe the sea ice characteristics of the Parry Channel to improve this understanding.

1.2 Objective

The objective of this thesis is to analyze the sea ice characteristics of the Parry Channel. This is accomplished in three steps:

1. To describe the break-up, movement, and freeze-up patterns of the sea ice cover of the Parry Channel.

2. To describe the oceanographic and atmospheric environment of the Parry Channel.
3. To combine the results of the above two analyses to describe the sea ice regime characteristics of the Parry Channel.

1.3 Study Area

This thesis studies the Parry Channel which includes the waterways of Lancaster Sound, Barrow Strait, Viscount Melville Sound, M'Clure Strait and Prince of Wales Strait (Figure 1.1). The adjoining channels and waterbodies are discussed to the extent that these channels affect the ice regime of the Parry Channel.

1.4 Thesis Organization

This thesis comprises six chapters. In this introduction, the thesis objective along with a description of previous work related to the objective are discussed. In Chapter 2 the method followed in this analysis, as well as the strengths and weaknesses of data sources used, are described. The oceanographic and atmospheric environment of the Parry Channel are described in Chapter 3. In Chapter 4, sea ice break-up, movement, and freeze-up patterns of the Parry Channel are described. In Chapter 5, ice regimes and sub-regimes of the Parry Channel are identified. Conclusions and recommendations of this study are in Chapter 6.

Figure 1.1: Site map

Figure 1.1 Site Map Legend:

1. Philpots Island
2. Navy Board Inlet
3. Croker Bay
4. Cape Charles Yorke
5. Cape Crauford
6. Baillarge Bay
7. Nanisivik
8. Prince Leopold Island
9. Resolute Bay
10. Griffith Island
11. Lowther Island
12. Young Island
13. Garrett Island
14. McDougall Sound
15. Polaris
16. Little Cornwallis Island
17. Milne Island
18. Crozier Island
19. Pullen Strait
20. Queen's Channel
21. Maury Channel
22. Baillie Hamilton Island
23. Pioneer Channel
24. Norwegian Bay
25. Byam Martin Island
26. Byam Channel
27. Ile Vanier
28. Prince Gustaf Adolf Sea
29. Franklin Strait
30. Cape Russell
31. Cape Vesey Hamilton
32. Edglinton Island
33. Fitzwilliam Strait
34. Cape Meham
35. Griffiths Point

1.5 Previous Work

A number of investigations into the ice environment characteristics of the Canadian high Arctic have been undertaken and are available in the open literature. These studies commonly take one of two forms. One form is that of an ice atlas which consists of a series of maps illustrating the progressive change in the ice cover based on the summary of a number of years of ice reconnaissance. The second type of study available in the literature are contract reports and journal publications which form a written analysis of the ice environment over a pre-defined area of the high Arctic.

1.5.1 Ice Atlases

One of the first ice atlases of the high Arctic was the *Ice Atlas of the Northern Hemisphere* produced by the U.S. Navy in 1946 (U.S. Navy 1946). This atlas comprises a series of small scale maps of the entire northern hemisphere for each month of the year. Due to the small scale of the maps, limited detail is available for the Parry Channel. The U.S. Navy atlas was based primarily on data collected from historical accounts from ships logs as well as some very limited aerial reconnaissance. Despite the limited information that was available on the environment of the high Arctic in the mid-nineteen forties, a number of the macro characteristics of the ice of the high Arctic are identifiable in the atlas including: the expansion of the north water polynya between Greenland and Ellesmere Island in April, the early clearing of Lancaster Sound in June compared to areas to the east or west and the identification of the average location of the eastward spring consolidated ice edge for the Parry Channel at Prince Leopold Island. A limited assessment of navigation was made in this atlas for the high Arctic. The area from southern Davis Strait in the east to the Bering Sea to the west was identified as unnavigable from November to April with some navigation possible west of Resolute Bay by

powerful icebreakers in the summer months. This pessimistic view of navigation has been refuted in recent years with several voyages by Canadian icebreakers into the eastern Parry Channel in November and December (Gorman 1985, 1987) as well as non-icebreaking vessels west of Resolute in the summer months (de Bastiani 1986).

8. The first comprehensive analysis of the ice of the Canadian high Arctic was entitled *Ice Atlas of Arctic Canada* (Swithenbank 1960). This atlas was a joint undertaking between the Canadian Defence Research Board and the British Scott Polar Institute. The Swithenbank atlas did not attempt to show average or normal conditions but, rather, attempted to summarize all available ice observations for the high Arctic from 1900 to 1958. All observations from ships, shore, and aircraft were summarized onto a 55 nautical mile grid system covering the area from Baffin Bay to the Beaufort Sea from March 1 to November 30. The atlas comprises a series of weekly maps reporting total ice concentrations along with a code identifying the extent to which this ice would impede marine navigation. Ice concentrations up to five tenths were considered navigable by all vessels while concentrations in excess of eight tenths were navigable only by icebreakers and consolidated ice was considered unnavigable. This was a simplistic view of navigation as no attempt was made to separate the effect of differing ice types (i.e., young or old) on navigation and presented an overly pessimistic assessment. This restricted view on vessel capability in ice was likely due to the inability of shipping at that time to deal effectively with navigation in ice covered waters. According to this atlas, navigation for icebreakers was possible from late June to early September in the Parry Channel. The reason for identification of such a narrow window was likely due to the limited amount of data used in the atlas. Ship reports of ice conditions were confined to the period from the first week of August to the end of the first week of September. In addition, large, powerful, icebreakers were just being developed at the time of atlas publication, with most shipping

unable to contend with high concentrations of sea ice. More recent experience with large modern icebreakers has proven this window to be too constrictive. The Swithenbank atlas indicates how limited the data base on sea ice and navigation was for the Canadian high Arctic by 1960.

The limited knowledge base on the environment of the high Arctic was well recognized by the Canadian Government which established the Polar Continental Shelf Project (P.C.S.P) in 1960. One of the first mandates of the project was to collect comprehensive data on the ice of the Canadian high Arctic (D. Mudry, Chief Ice Climatology, A.E.S., pers. comm., 1987). The P.C.S.P undertook a series of aerial ice reconnaissance flights between June and October for the years 1961 to the present. The results of these overflights were compiled into a three volume *Sea Ice Atlas of Arctic Canada* (Lindsay 1975, 1977a, 1981). Very little analysis or discussion of the results of these reconnaissance flights is provided in the atlas. Each volume of the three volume set contains short subjective, written analysis of each year. A short summary report for the period from 1961 to 1974 was prepared which described the break-up and freeze-up pattern for each year (Lindsay 1977b).

The Lindsay atlases were of limited value for this investigation. These atlases are primarily a compilation, in book form, of all P.C.S.P. observed charts. Since these charts are also present in the archives of ice reconnaissance observed charts stored at Ice Climatology Atmospheric Environment Service (A.E.S.), they were analysed in the course of data analysis undertaken for this thesis (see Section 2.3). Consequently, it was redundant for this author to analyze the Lindsay atlases as the charts presented in the Atlas had already been viewed in the archive.

The most recent and comprehensive ice atlas covering Arctic Canada is the *Ice Atlas: Canadian Arctic Waterways* (Markham 1981) produced by the Atmospheric Environment Service (A.E.S.). The primary data source used for this atlas was ice charts produced by A.E.S. between 1959 and 1974. Ice concentrations for first year

and old ice were digitized onto a 30 nautical mile grid covering the entire Arctic from Davis Strait to Point Barrow, Alaska. Weekly ice maps were produced for the period from May 21 to October 29. Maps were produced illustrating minimum and maximum reported ice concentration for each square for each week. Additional maps showing median reported ice concentration and the concentration of old ice for each square were also produced. A short written summary is included at the beginning of the atlas describing general patterns of ice break-up, movement and freeze-up for the high Arctic.

The Markham Atlas has become one of the most referenced sources of information available describing the distribution of sea ice for the high Arctic. The written description at the beginning of the atlas is a valuable general summary of patterns of ice distribution in the high Arctic. The total ice concentration maps in the atlas show many general patterns and trends of ice distribution for the high Arctic also found in this study. However, there are a number of limitations to the Markham atlas, particularly pertaining to old ice distribution. The primary source of information for the maps were observed ice charts and Markham states that a high degree of variation occurs in the accuracy of these data (Markham 1981). In the interpretation of observed charts contained in the A.E.S. archive undertaken for this study, a great deal of variation in the consistency of reporting of old ice was found by this author for many areas. For example, it was found that the reported concentration of old ice in a consolidated ice area often varied by several tenths or more over successive surveys even though the ice cover remained consolidated. Therefore, when these data were statistically averaged into the grid squares (by Markham), these inaccuracies were incorporated into the data base. This resulted in maps of old ice distribution that show confusing patterns of concentration and distribution. Such errors make conclusions on old ice occurrence in the high Arctic difficult to draw from the Markham atlas. For example, the weekly maps of the median average distribution of old ice for central Viscount Melville Sound for the

period from May 21 to the beginning of July show a high degree of variation. If one considers that this area is always consolidated during this period (Markham 1981), then the variation in old ice distribution should occur between years and not within years. Therefore, the median distribution of old ice from May 21 until break-up should be the same for each week. Thus, the wide variation in median values recorded on the maps for this period can only be the result of inaccurate raw data. It is more difficult to assess the effect of these erroneous data on other maps in the atlas which show areas that have within year as well as between year variations (i.e., unconsolidated areas). Therefore, the use of the Markham atlas is greatly limited by these inaccurate input data such that most patterns of ice distribution depicted by the atlas may be imaginary as much as real.

1.5.2 Open Literature

The majority of works contained in the open literature as journal publications and contract reports describing the ice of the Parry Channel may be summarized as having been the result, either directly or indirectly, of three major Arctic development programs:

1. The Arctic Pilot Project (APP).
2. The EAMES (Eastern Arctic Marine Environmental Studies) Program and,
3. The M.V. Arctic Program.

The objective of the Arctic Pilot Project (APP) was to test the feasibility of producing and transporting liquefied natural gas (LNG) by two large icebreaking LNG tankers, from Bridport Inlet, Melville Island, N.W.T., to regasification plants in southern Canada on a year-round basis (see Figure 1.2). The APP proponents had expected to transport 50 billion m^3 of gas during the 20 year life of the project (APP 1981). The APP, officially announced by Petro-Canada in early 1977, had

Figure 1.2: Location of major development projects in the Parry Channel

expected to commence shipments in 1985. However, the oversupply of natural gas in Canadian markets by the early 1980's led the National Energy Board to defer the Project indefinitely in the fall of 1983. Nonetheless, sea ice studies undertaken by the APP and related government and private agencies between 1977 and 1981 represent one of the largest and most extensive source of ice environment data and analyses available in the literature for the Parry Channel region.

Many of the major studies initiated by the APP were in the summer and fall of 1977 and consisted of a series of detailed, low level ice reconnaissance flights in the Viscount Melville Sound area. These surveys were supplemented by an analysis of five years of NOAA and Landsat satellite imagery as well as historical ice observations to typify the ice conditions leading to the loading terminal on the south coast of Melville Island (NORCOR 1978). Additional surface-based studies to document ice thickness as well as first year ice ridge distribution and profiles were undertaken in Viscount Melville Sound in the spring of 1978 (Comfort, Edwards 1978, Intera 1978). Further studies, continued by the APP between 1978 and 1981, included the study of the ice fracturing of Barrow Strait and further ridge studies and ice strength measurements in Viscount Melville Sound to estimate the effect icebreaking may have on consolidated ice regimes of these areas (Acres 1981, Perchanok *et al.* 1981, Fenco 1981, Hotzel and Nobel 1979). All APP ice studies were undertaken between April and early November. It was felt that the conditions documented in October and early November typified winter conditions for the Parry Channel (NORCOR 1978). Additional studies monitoring winter conditions from five years of NOAA VHRR imagery were also undertaken by APP, government, and universities (Marko 1977, 1978, Smiley and Milne 1979).

The vast majority of ice studies undertaken for the APP were concentrated in the Viscount Melville Sound and Barrow Strait area of the Parry Channel. The major conclusions drawn from the APP studies were that the most arduous ice conditions to be faced by tankers were to be found in western Barrow Strait and

northern Viscount Melville Sound. The existence of heavily ridged first year ice and the flow of old ice southward from Byam Martin Channel were thought to be the major obstacles to be overcome. The only serious limitation to navigation recognized for the eastern Parry Channel east of Resolute Bay was the existence of high iceberg concentrations at the entrance to Lancaster Sound (APP 1981).

The second major thrust of research on the ice environment of the Parry Channel came with the Petro-Canada-EAMES program in 1978-79. The purpose of this program was to collect detailed information on the physical environment of Lancaster Sound so that an assessment of the impact of exploratory drilling for hydro-carbons could be made (Marko 1982). A number of sea ice studies were undertaken in support of the objective and, like the APP project, were undertaken between April and October. The data collected by the EAMES program of ice motion from satellite imagery and ocean ~~currents from~~ drifter buoys, presently form much of the knowledge base at the entrance to Lancaster Sound (Fissel, Lemon, Birch, 1981, Marko 1982). Although sea ice studies were undertaken, the primary effort was directed to the study of icebergs in the eastern Arctic as these were recognized as the only serious threat to summer offshore drilling in the area (Marko 1982).

The most recent information on the ice environment of the Parry Channel is from the M.V. Arctic program which began with the creation of the Canarctic Shipping Company Limited (a consortium of Federal Government and private industry) in 1975. The primary objective of Canarctic was to develop Canadian leadership in year-round Arctic marine transportation arising from the development of significant lead-zinc mineral deposits in the high Arctic (Luce et al. 1987). To meet this objective, Canarctic owns and operates the M.V. Arctic, a 28,000 DWT (dead weight tonne) icebreaking oil and dry bulk cargo vessel delivered from the Port Weller Dry Docks at St. Catharines, Ontario, in 1978. The purpose of M.V. Arctic is to act as an operational test bed for research into all aspects of

ship navigation in the early spring, fall and winter periods in the high Arctic. The M.V. Arctic is constructed to Canadian Arctic Shipping Pollution Prevention Regulations (ASPPR) Arctic Class 4 specifications.

The M.V. Arctic has acted as the principal carrier of lead-zinc cargo from the Nanisivik mine, located on the northern tip of Baffin Island, and the Polaris mine, located on the south-western shore of Little Cornwallis Island. The M.V. Arctic also carries crude oil from the Panarctic Bent Horn oil facility on Cameron Island (see Figure 1.2). The M.V. Arctic, being an icebreaking vessel, has more than doubled the navigational period within the Parry Channel, from late May to early December. In order for such a season extension to be possible, an intensive research program into the ice environment and navigation has been required (Luce *et al.* 1987).

Early studies in the M.V. Arctic program concentrated on studying consolidated ice conditions leading to the Nanisivik and Polaris mines in the spring period. Detailed remote sensing studies and thickness and strength measurements were carried out on the ice of Admiralty Inlet, leading to the Nanisivik mine (Madison 1981, Lapp 1983(a), Lapp 1983(b), Lapp and Wells 1983) and McDougall Sound, leading to the Polaris mine site (Embacher 1982, Lapp 1983(b), Lapp 1984). Coincident with these studies there began, in 1983, a dedicated series of shipborne studies to develop new navigation techniques for ice and a program of vessel performance evaluations. These studies provided a great deal of new information on the nature and distribution of sea ice in the eastern and central Parry Channel (Wells *et al.* 1984(a), 1984(b), 1985, Sneyd 1983, 1984, Gorman 1985, 1986, 1987(a)). Additional studies of satellite and SAR imagery were undertaken to gather further details on the ice environment of specific areas within the Parry Channel (Lapp 1982, de Bastiani 1986, Gorman 1986, Atcheson 1985, Intera 1986, Lapp *et al.* 1986). Unlike previous programs, such as the APP, which studied ice conditions for April to late October, the M.V. Arctic program has studied

all months of the year and included shipborne field trials into December at the eastern entrance to Lancaster Sound (Gorman 1987(b)). Contrary to the findings of the APP that few sea ice related hazards existed in the eastern Parry Channel (APP 1981), shipborne experience on the M.V. Arctic has demonstrated that difficult conditions do, indeed, occur. For example, the movement of high concentrations of old ice (up to seven tenths) into the eastern entrance of Lancaster Sound in November and December creates difficult ice conditions for surface vessel transit. This has been found to be due to the combined effect of strong surface water currents with high old ice concentrations in large floes in a developing first year ice matrix, a situation which severely limits a large vessel's manoeuvrability (Sneyd 1983, Gorman 1985, 1987(b)). Unlike the APP, which assumed that ice conditions measured in the Parry Channel in the late October and early November period typified winter conditions (NORCOR 1978) the M.V. Arctic program has demonstrated that winter conditions are very dynamic, particularly in the eastern region, such as conditions relating to the movement of old ice through the Channel (Atcheson 1985, Intera 1986, Gorman 1987(b)). Additional findings from the M.V. Arctic program include the documentation of much more severe first year ice ridging in the Lancaster Sound region in the early spring when consolidated conditions prevailed than had been expected previously for the eastern Parry Channel (Wells et al. 1987).

The findings of the M.V. Arctic program are due to three major factors:

1. The recent availability of a high quality remote sensing data set from synthetic aperture radar (SAR) (see Section 2.4.5) which depicts ice conditions not previously identified from other sensors,
2. The operational experience and measured performance of a large commercial icebreaker in the various ice conditions and,

3. The availability of more than twice as many years (i.e., 13 years) of NOAA AVHRR imagery than available to APP investigators.

Based on the author's experience during season extending voyages onboard the M.V. Arctic, it had become evident that a thorough understanding of the nature of the ice environment was required if year-round navigation in the Parry Channel was to become a reality. Despite efforts of the M.V. Arctic program, much remains unknown about the ice regime characteristics of the Parry Channel. Although numerous regional studies have been carried out using the large volume of satellite imagery and SAR data as part of the M.V. Arctic program, no study has yet analysed the entire Parry Channel simultaneously. Therefore, it was the intent of this thesis to undertake such an analysis. From this study, a number of recommendations on areas where knowledge is lacking and where future work should be directed are presented.

Chapter 2

Methods

2.1 Introduction

The purpose of this thesis is to describe and analyze the sea ice characteristics of the Parry Channel. In order to accomplish this goal, three tasks were completed. In this chapter the methods of analysis, along with the data sources used, will be described.

The tasks completed for this thesis were as follows:

Task #1 - Physiography, Oceanography and Climatology Review

In order to attempt an analysis of the ice behaviour knowledge of the physiography, oceanography and climatology that serve to create and drive the sea ice of the region was required. Therefore, a review of major studies on the physical environment of the Parry Channel was undertaken. A summary of the physical environment characteristics of the Parry Channel is described in Chapter 3.

Task #2 - Historical Review

A detailed analysis of satellite imagery and Atmospheric Environment Service (A.E.S.) ice charts of the study area was undertaken for the period from January 1974 to December 1986 to define the ice break-up, movement, and freeze-up patterns for the channel. The results of this review are described in Chapter 4. The

attributes and limitations to the data sources used in this analysis are described in section 2.2 of this chapter. The data sources used in the historical review were:

- a) NOAA VHRR and AVHRR satellite imagery
- b) Ice Reconnaissance, A.E.S., observed charts,
- c) Ice Forecasting, A.E.S., current charts, and
- d) Ice Forecasting, A.E.S., composite charts.

Task #3 - Analysis of the Ice Regime Characteristics of the Parry Channel

The purpose of this task was to combine the patterns of ice formation, movement, and decay, (identified in task #2) with physical environment data (from task #1) to identify and attempt to explain the patterns of ice behaviour in the Parry Channel. It was hoped that such a description of the sea ice environment of the Parry Channel would reveal the major features that potentially could affect, both positively and negatively, year-round marine navigation. This analysis is presented in Chapter 5.

The analysis undertaken for Task #3 is based on describing the "ice regime" characteristics of the Parry Channel. The term "regime" is a noun used to describe a complex method or system of operation (Hawkins 1981). It is most commonly used to describe political systems or governments. More recently, this term has been applied to describe complex systems in the natural environment (Hayward and Sparkes 1981). In this thesis, the term "ice regime" is used as a noun to identify a water body of defined geographic area that has a unique system of sea ice growth and movement that is distinctive from other surrounding regions. In order for an "ice regime" description to be complete, more than just a simple description of the ice environment was required. A description of environmental

variables that serve to create and drive the ice was also required. Only through this full description can the "method" or "system" of operation be fully understood.

In the analysis of the ice cover of the Parry Channel, undertaken for this thesis, a number of consistent patterns of ice distribution and movement were identified from year to year within the region. Based on these identified patterns, combined with a basic understanding of the environment, the boundaries of the ice regimes of the Parry Channel were identified. In addition to the identification of ice regimes, sub-regime regions of the Parry Channel were also identified. These sub-regime areas, although following the general characteristic of the ice regime, had at least one unique ice behaviour characteristic. The definition of these regimes and sub-regimes was the primary goal of this thesis and the description and justification for the chosen boundaries are presented in Chapter 5. The description of the method followed in delineating ice regimes and sub-regimes is described in section 2.3 of this chapter.

2.2 Historical Review Methods

An essential step in achieving the objective of this thesis was to review the year-by-year variability of the sea ice break-up, movement and freeze-up patterns for the study area. This was accomplished by a review of data stored in the archives of the Ice Climatology Section of the Atmospheric Environment Service, Environment Canada.

A great deal of effort was placed on using only data of the highest quality. As discussed in the review of previous work, in Section 1.5, erroneous information leads to erroneous conclusions on sea ice distribution. It is the opinion of this author that the most accurate information available concerning sea ice of the high Arctic has been acquired only since the widespread use of remote sensing devices for ice reconnaissance came into practice. The first significant milestone in this

regard came with the launch of the Very High Resolution Radiometer (VHRR) on ITOS (Improved TIROS Operational Satellite) by the American National Oceanographic and Atmospheric Administration (NOAA) in 1970. Data from this sensor came into operational use for ice reconnaissance and the production of A.E.S. ice charts shortly after launch. An extensive archive of VHRR imagery (subsequently called NOAA imagery) of Canadian ice covered waters was begun in 1974 by A.E.S. and continues to the present day. Prior to the launch of the VHRR sensor, ice reconnaissance relied solely on airborne and ship-based ice observers. The quality of these data is highly variable and, consequently, the review of historical ice information undertaken for this thesis has used satellite and ice chart information only since 1974.

The historical review undertaken for this thesis utilized the large archive of NOAA satellite imagery as well as three forms of ice charts produced by A.E.S. since 1974: the Observed Ice Chart, produced by government of Canada ice observers stationed onboard aircraft and ships; Current Ice Charts, which are prepared by Ice Forecasting Meteorologists of A.E.S. and, Composite Ice Charts which are weekly charts also produced by Ice Forecasting Meteorologists. The description of each data source used in the historical review is summarized in Section 2.4, Data Sources and Limitations.

The review process comprised a number of steps. The first step involved sorting through the vast archive of NOAA satellite imagery to select the clearest images covering the study area for each month from January 1974 to December 1986. The approximately three thousand five hundred images selected were then visually analyzed, image by image, in chronological sequence to identify the dates of major events such as ice bridge formation or fracture, occurrence of consolidation or mobility, as well as patterns and sources of ice movement. A short written summary was generated for each of the thirteen years of the study which included maps of major patterns of ice distribution as well as a table of dates for main events.

Although NOAA satellite imagery provides a good regional picture of ice behaviour, high levels of confidence cannot be placed on the identification of all ice types, particularly the separation of thicker forms of first year ice and old ice (see Section 2.4.1). Therefore, as a second step in the analysis, ice charts produced by A.E.S. ice observers stationed on aircraft and surface vessels were also analyzed in conjunction with the satellite imagery. Observed ice charts are produced for all Canadian ice covered waterways and report ice concentration by thickness, age and floe size using standard coding contained in MANICE (1980).

The observed charts are stored in the Ice Climatology archive along with other ice chart products produced by the Ice Forecasting and Analysis section of Ice Centre. These charts are stored in large folios of approximately five hundred charts each covering a specific area of the Canadian high Arctic for each year. Three folio sets were analyzed: Northern Baffin Bay-Nares Strait, Approaches to Resolute and the Queen Elizabeth Islands. The analytical procedure involved studying each chart in each folio that covered the Parry Channel, recording in note form, the occurrences of old ice as well as dates of major events such as the occurrence of consolidation or fracture. A great deal of caution was used when interpreting the age reports on the observed charts. As noted in the section on data sources and limitations (2.4.2), the accuracy of observed charts is suspect. However, the observed charts did provide a general indication of the age distribution of the sea ice for the Parry Channel at various times of the year.

The third and final step in the historical review involved summarizing the year by year analysis from the NOAA satellite images and A.E.S. charts into a description of the ice break-up, movement, and freeze-up patterns as well as a description of the old ice sources and movement. This summary comprises Chapter 4 of this thesis.

2.3 Ice Regime Definition

The definition of the geographic boundaries of ice regimes and sub-regimes of the Parry Channel was the primary aim of this thesis. This objective was accomplished by combining the analysis of ice break-up, movement, and freeze-up characteristics, undertaken during the historical review phase of the study, with basic physical environment characteristics of currents, tides, and climatic elements of the Channel. A number of common patterns of ice behaviour of the Parry Channel became evident as a result of this analysis which aided in the identification of the characteristics of ice regimes and sub-regimes. These characteristics include the timing and pattern of break-up, the uniform movement of ice through the area, the timing and pattern of freeze-up, as well as the presence and movement of old ice. Three criteria were used in delineating the various regimes and sub-regimes. These were:

1. The quantity and distribution of first year ice throughout the year based on the following analysis:
 - a) Is first year ice the dominant ice type in the area?
 - b) Is the first year ice apparently thicker or thinner in the area than surrounding areas?
 - c) Does fracture and/or consolidation occur as an identifiable pattern separate from surrounding areas?
2. The quantity and distribution of old ice throughout the year:
 - a) Is old ice the dominant ice type?
 - b) Does old ice occur perennially or is it seasonally-transient?
 - c) Is this area an important or geographically distinct birth place for old ice?

- d) Is there a definable boundary of old ice transport through this area that may serve to define a regime boundary?
3. The identification of oceanographic or climatic features distinctive to a specific area that may help to explain the ice behaviour including:
- a) Is there a strong surface water current or currents in an area that will move the sea ice in a way that may define a regime boundary?
 - b) Is there a water mass boundary or mixing area that may alter the sea ice characteristics of an area thereby creating an ice regime boundary?
 - c) Is there a shoaling of tidal energies in particular areas that may serve to modify the overlying ice cover?
 - d) Is there a variation of climatic variables such as air temperatures and winds that may alter the sea ice characteristics of an area?

For the purpose of this thesis, the distinction between different ice regimes required differences in all of the above criteria. A sub-regime was an area where one of the above criteria was dominant compared to surrounding sub-regimes but that the area had ice characteristics similar to the main ice regime. The analysis of the ice regime of the Parry Channel, including discussions of each of the above mentioned criteria, is included in this thesis as Chapter 5.

To aid in the delineation of these ice regimes and sub-regimes, three sets of synthetic aperture radar (SAR) imagery were used in the analysis and included in Chapter 5. This SAR imagery is of a high resolution and provides detail on ice regime characteristics not available from other data sources. A description of the strengths and weaknesses of this sensor is presented in section 2.4.5 of this Chapter.

2.4 Data Sources and Limitations

As mentioned in the description of the historical review process (Section 2.2) a great deal of effort was made to use only data of the highest quality for this analysis. In this section, each data source used will be described and the strengths and limitations of each source discussed. A summary of the advantages and disadvantages of each data set used in this thesis can be found in Table 2.1.

2.4.1 NOAA Satellite Imagery

The National Earth Satellite Service (NESS) of the American National Oceanic and Atmospheric Administration (NOAA) operates a network of geostationary and polar orbiting environmental satellites. The satellite series of most interest to ice information users is the TIROS satellites (Television Infra-red Observations Satellite). The TIROS series began operation with the launch of the TIROS-1 in 1960. The primary sensor package on the early TIROS was a television type camera called the Return Beam Vidicon (RBV) with data being transmitted to earth via a VHF (very high frequency) APT (automatic picture transmission) service operating in the megahertz frequency.

A major change in the design and operation of the TIROS satellites, and the one of most importance to ice reconnaissance, came with the ITOS (Improved TIROS Operational Satellite) in 1970. The RBV sensor was replaced by a two channel electronically scanning radiometer, the Very High Resolution Radiometer (VHRR). Concurrent with the VHRR was the addition of the High Resolution Picture Transmission (HRPT) service. Due to the high data volume generated by the VHRR sensor, a wide band width gigahertz frequency data bus was required from the satellite to ground stations and this was met with the HRPT. With the launch of ITOS-2 in 1972, the operational name of the satellite series was changed from TIROS to NOAA. The ITOS series of satellites were launched as NOAA-2 to

Table 2.1
Data used for Historical Review
Advantages and Disadvantages

Data	Source	Advantage	Limitation
1) NOAA (AVHRR) - Infra-red - Visual	Ice Climatology - Ice Centre archived from: 1) Arctic Weather Centre-Edmonton 2) Nook-Greenland 3) U.S.A. Navy-Alaska	1) Repetitive coverage, often several times a day. 2) Large area coverage. 3) Adequate resolution (1km) for the detection of major ice features. 4) Visual band and reflected IR useful during summer open water period. 5) Thermal IR useful during fall and winter period to penetrate darkness.	1) Cloud cover often for several weeks at a time particularly during July, August and September. 2) Variation in quality of photographic products in archive. Age deterioration and tonal variations. 3) Ice type, particularly old ice, not adequately determined from NOAA images.
2) Composite Charts	Ice Climatology archive from Ice Forecasting and Analysis.	1) Continuous weekly coverage over all of study area.	1) Inconsistency in ice type report, often different ice type designations are assigned to a consolidated ice regime over a 2 or 3 week period. 2) Unknown source and accuracy of input information. 3) Lack details of observed charts.

Data	Source	Advantage	Limitation
3) Current Ice Chart	Ice Climatology archive from Ice Forecasting and Analysis.	1) More detailed than composite charts. 2) Frequently available for Parry Channel in successive days during shipping season. 3) Known source of input information.	1) Absent outside of shipping season. 2) Few charts produced for areas west of central Barrow Strait.
4) Observed Ice Chart	Ice Climatology archive from Ice Reconnaissance.	1) Detailed reporting of ice type and concentrations. 2) Useful when satellite information not available.	1) Sporadic coverage, may be absent for long periods, particularly in fall and winter. 2) Inconsistency in ice type reporting - often ice observations vary widely over same area during same period.
5) STAR 1/2 SAR	By contract from Intera Technologies Limited.	1) High resolution all weather detail of ice cover. 2) Very good resolution and detection of even very small old ice floes.	1) High cost and limited availability. 2) Thin ice leads and the separation of mobile from consolidated ice somewhat more difficult than with the AVHRR sensor.

NOAA-5 between 1972 and 1976. The VHRR sensor used on NOAA-2 to NOAA-5 was a two channel multi-spectral scanner (MSS) sensing in the visual and thermal infra-red regions with a swath width of 2580 km and a spatial resolution of 0.87 km (RESORS 1986).

The next generation of NOAA satellites, TIROS-N, was launched into service with NOAA-6 in 1979 and represents the present day NOAA series. Table 2.2 contains a listing of the NOAA satellites which produced images used in the historical review undertaken for this thesis. The VHRR of the ITOS series was replaced by the Advanced Very High Resolution Radiometer (AVHRR) on the TIROS-N series. The AVHRR is a five channel MSS sensing in the visible, reflected infra-red and thermal infra-red regions of the spectrum with a swath width of 2700 km. In Table 2.3 can be found a summary of the VHRR and AVHRR sensor characteristics. The AVHRR sensor has two series, the AVHRR-1, used onboard NOAA-6 and the AVHRR-2 used on subsequent NOAA satellites. The AVHRR-1 was an experimental version and lacked the fifth (11.5-12.5 μ m) thermal infra-red channel of the AVHRR (Barns and Smallwood 1982).

The NOAA satellite imagery used in this thesis were collected by the VHRR from the ITOS series of satellite (NOAA-2 to 5) and the AVHRR from the TIROS-N series (NOAA-6 to 9). These data are held in the archive of the Ice Climatology Division of Ice Centre, A.E.S.. The Ice Climatology archive contains satellite images derived from four satellite ground receiving stations:

1. The Arctic Weather Centre, A.E.S., Edmonton, Alberta,
2. The Canadian Meteorological Centre, A.E.S., Downsview, Ontario,
3. The Danish Weather Centre, Nook, Greenland, and
4. The United States Navy Satellite receiving station at Fairbanks, Alaska.

Table 2.2

**NOAA Satellites Producing Images Used for
the Historical Review**

Satellite	Series	Launch Date	Ceased Operation	Primary Senior
NOAA-2	ITOS	15/10/72	19/03/77	VHRR
NOAA-3	ITOS	06/11/73	17/12/74	VHRR
NOAA-4	ITOS	15/11/74	15/09/76	VHRR
NOAA-5	ITOS	29/08/76	01/03/79	VHRR
NOAA-6	TIROS-N	27/06/79	05/03/83	AVHRR/1
NOAA-7*	TIROS-N	23/06/81	-----	AVHRR/2
NOAA-8*	TIROS-N	28/03/83	-----	AVHRR/2
NOAA-9	TIROS-N	12/12/84	-----	AVHRR/2

* NOAA 7 and 8 have experienced several temporary orbital failures resulting in periods of inoperation (Adapted from RESORS 1986).

Table 2.3
VHRR and AVHRR Sensor Characteristics

VHRR

Channel	Resolution	Wavelength	Swath Width
1	.87 km	.6-.7 μm	2580 km
2	.87 km	10.5-12.5 μm	2580 km

AVHRR

Channel	Resolution	Wavelength	Swath Width
1 *	.5 km	.58-.68 μm	2700 km
2	.5 km	.725-1.10 μm	2700 km
3	.5 km	3.55-3.93 μm	2700 km
4	1.0 km	10.5-11.5 μm	2700 km
5 **	1.0 km	11.5-12.5 μm	2700 km

* AVHRR/1 .58-.90 μm

** AVHRR/1 Lacked channel 5

(Adapted from RESORS 1986, Barns and Smallwood 1982)

Satellite images from the NOAA series came into operational use for ice forecasting and analysis at Ice Centre, A.E.S., in 1974. Since that period, all satellite images of Canadian ice covered waters received by the above mentioned stations are transmitted by telephone facsimile to Ice Centre. In addition, the same images are subsequently mailed, as nine and one half inch square photographic prints, to Ice Centre for inclusion in the Ice Climatology satellite image archive. Thus, the Ice Climatology archive contains an extensive collection of satellite imagery of ice covered waters of Canada for the period from January, 1974, to the present. This archive was the source of all satellite images used in the historical review.

The images contained in the archive are at one of two scales. Most images are regional images of the Canadian Arctic and east coast of Canada at 1:11 million scale. However, the Edmonton and Downsview stations also produce image enlargements at 1:4 million scale.

The satellite images sent to Ice Centre are enhanced for ice detection at the receiving stations. During the late spring and summer months, visual band images provide the best detail of ice condition when sea ice stands out starkly against dark open water. A simple linear contrast stretch is applied to the visual images to enhance detail in the brighter returns from sea ice. Images produced from the thermal infrared channel of NOAA satellites show little contrast between open water and sea ice during summer months since the sensible temperature difference between ice and open water is very small (i.e., near 0°C) during this period. However, as twenty-four hour darkness approaches for the high Arctic, in early November, the usefulness of visual band images drops sharply while thermal infrared images improve. As Arctic air temperatures drop, the temperature of the ice cover drops accordingly while open water areas remain near 0°C . Consequently, thermal infra-red images show good contrast between open water (warm), grey to grey-white ice (cool) and thick first year and old ice (cold) throughout the winter darkness. During the winter period, satellite receiving stations send enhanced

thermal infra-red channel NOAA images to Ice Centre for ice analysis and storage.

The quality of the satellite images held in the Ice Climatology archive are generally similar from year to year. Visually, there was little to no detectable difference noted between images collected by the VHRR (NOAA-2 to 5) for 1974 to 1979 and those collected by the AVHRR (NOAA-6 to 9) collected between 1979 and 1986. Although the AVHRR produces higher quality digital data than the VHRR (Barns and Smallwood 1982), the primary limitation on the data quality used in this study was the photographic print medium. Although the full digital resolution of these sensors is in the 1 km range, the apparent resolution of these 1:11 million and 1:4 million photographic prints was likely somewhat lower, probably in the 3 to 4 km range.

NOAA satellite images were of most use in documenting ice conditions during the late fall and winter. During the winter months, little cloud cover occurs in the high Arctic and this, combined with darkness penetration capabilities of thermal channels, resulted in an extensive data set of satellite images during the period. However, during the summer months, when cloud cover and storm activity is the most intense, NOAA satellite images would often be absent for periods of several weeks at a time. Consequently, extensive cloud cover formed the major limitation of this data source.

It has been found by this author, based on field experience using NOAA satellite imagery, that the following conditions must be met in order for ice to be detected on NOAA imagery:

1. Ice thickness of at least grey ice (10 cm or more),
2. Ice occurring in concentrations of at least 2-3 tenths over a three to five nautical mile area.

New ice (less than 10 cm in thickness) will generally not appear on NOAA satellite images. Although it is often possible to separate grey and grey-white ice

from first year and old ice due to the darker appearance of the former, confident separation of thick first year ice from old ice is generally not possible on both visual band or thermal infra-red images, since they appear equally bright.

2.4.2 A.E.S. Observed Ice Charts

Observation and recording of ice conditions over Canadian waters is the responsibility of Ice Reconnaissance Division of A.E.S.. The reconnaissance of Canadian ice covered waters began in the late 1950's and was part of a larger ice information program administered by the Federal Department of Transport. The responsibility for the operation of ice reconnaissance in Canada was transferred from Transport Canada to Environment Canada in 1970. Ice Reconnaissance underwent a major expansion in the mid-1970's when two long range Loughheed Electra aircraft were placed into ice reconnaissance service. In 1978 one of the Electras was fitted with a Motorola APS-94E SLAR system with the second aircraft being fitted with a similar SLAR system in 1985.

Stationed onboard the ice reconnaissance aircraft as well as on Canadian Coast Guard icebreakers are 25 to 30 ice observers. The primary function of the ice observer is to produce a chart of observed ice conditions along the plane's or ship's route. In the case of an aircraft fitted with an imaging SLAR system, these charts also include an interpretation of the SLAR data onto the chart. Observed Ice Charts are produced at a scale of 1:1 million and are the largest scale of any ice chart produced by A.E.S.. Ice coding terminology used in reporting ice conditions by ice observers on observed ice charts follows an international standard defined by the World Meteorological Organization (WMO) and is defined in MANICE (1980). The "egg code", so called due to the oval shape of the record, includes such descriptive designations as total ice concentration, ice concentration by age as well as floe size distribution. Additional information on ridging, snow cover and melt ponds may also be included where appropriate.

The observed ice charts produced by ice observers are transmitted directly to Ice Forecasting and Analysis Division of Ice Centre in Ottawa via HF (high frequency) facsimile. These charts, together with near-real-time NOAA and LANDSAT satellite imagery transmitted from the ground receiving stations, are used to produce synoptic ice charts called Current Ice Charts (see section 2.4.3). Upon completion of a current ice chart, the observed charts are transferred to Ice Climatology Division for storage in the respective folios of the archive. It is these charts contained in the Ice Climatology archive that were analyzed in the historical review task of this thesis.

The strength of observed ice charts lies in the detail available on the age and distribution of ice over a given area, even during periods of extensive cloud cover when satellite images are not available. Observed ice charts are the most numerous in the May to October periods for the Parry Channel with few charts available for winter months. This makes observed charts a good complementary source of ice information to NOAA satellite imagery which tend to be more available over the winter months due to the often large degree of cloud cover during the high Arctic summer. Therefore, information such as the dates of fracture or patterns of ice movement during the summer months were often gleaned from observed ice charts when satellite images were not available.

The primary limitation of observed ice charts stems from the, at times, variable accuracy of the charts. The classification presented on an observed chart is based on the subjective estimates of an ice observer that may be impeded by such factors as low sun angle, snow cover on the ice surface or poor visibility or variations in the quality of SLAR imagery produced onboard the aircraft. In this thesis, several observed charts collected of an area over successive surveys were used in the analysis so that this degree of variation could be assessed and taken into account.

2.4.3 Current Ice Charts

The primary operational product of Ice Forecasting and Analysis, A.E.S., is the current ice chart. These charts represent a synoptic analysis of ice conditions to be encountered over a selected water body and follow standard international ice reporting codes as defined by MANICE (1980) and are issued at a scale of 1:2 million. These charts are issued daily for Canadian ice covered waters where surface vessels are navigating. Current ice charts are issued for the Parry Channel between June and November of each year with most occurring between late July and early October.

A current ice chart is produced by an experienced ice forecasting meteorologist based on satellite, ice reconnaissance and meteorological information. Existing ice conditions recorded on observed ice charts, transmitted from ice reconnaissance aircraft, and interpreted from NOAA and LANDSAT satellite images transmitted from the ground receiving stations, are combined with forecast wind and temperature data, by the Ice Forecasting Meteorologist, to produce a current ice chart. This chart is transmitted via telephone line facsimile to Coast Guard marine radio stations for broadcast to surface vessels via marine HF radio facsimile. Upon completion of broadcast, current ice charts, along with observed ice charts, are transferred to Ice Climatology Division for storage in the archive. Current ice charts, stored in the archive, were used in the historical review undertaken for this thesis.

Current ice charts are more generalized than observed ice charts. This lesser amount of detail is due to the smaller scale of the current ice chart and the need to simplify the ice detail for transmission via marine facsimile. The primary advantage to this study of the current ice chart is that it provides a summary of ice information for a given area based on more detailed observed charts also present in the same folios in the archives.

The primary limitation of the current ice chart is that much of the information

used is based on observed charts, so that many of the inaccuracies of the observed chart will be carried over into the current ice chart. However, expert analysis of the ice forecasting meteorologist may serve to minimize error and this is detectable by the, at times, small discrepancies between ice types recorded on an observed chart to the resultant record on the corresponding current ice chart. Another limitation to the current ice chart is that it is only available for the period when ships are navigating in the Parry Channel, that is, from late July to early October in many years.

2.4.4 Composite Ice Charts

- In addition to current ice chart, the Ice Forecasting and Analysis Division of A.E.S. also produces the composite ice chart. The composite ice chart is produced once a week at a scale of 1:4 million for Canadian ice covered waters. Composite charts represent an estimate of the ice conditions for the area on the date of publication. Unlike current ice charts, composite charts are not broadcast over marine HF but are sent to users by mail on a subscription basis. The purpose of the composite chart is to act as a strategic planning tool. Due to the much smaller scale of composite ice charts, ice detail is more generalized than on other A.E.S. ice chart products. Ice data follows the same coding procedure as other A.E.S. charts as described in MANICE (1980). Two composite chart series were analyzed for this thesis: the Western Arctic Composite Chart covering central Barrow Strait westward to the Beaufort Sea and the Eastern Arctic Composite Chart covering Barrow Strait and Baffin Bay. Composite ice charts are produced for the Parry Channel region between May and December each year. These charts are stored in the archive of Ice Climatology A.E.S. in folios separate from other A.E.S. ice chart products.

The primary advantage of the composite ice chart is the continuous reporting of ice conditions over the Parry Channel at times when no other data source may

be available. These charts were referenced in the analysis for this thesis when NOAA satellite images were not available, such as during periods of extensive cloud cover, and when ice reconnaissance observed charts were also not available. However, there were several limitations to composite ice charts which made them a secondary data source for the historical review of this thesis. The small scale of the charts did not provide sufficient detail for patterns of ice behaviour for the Parry Channel to be determined adequately. In addition, they suffer from a small degree of inconsistency between charts in many cases. The accuracy of a composite chart is more difficult to assess than a current chart since, while a current chart will record the data sources used in a legend, the composite chart does not list the sources of information used.

2.4.5 STAR-1 and STAR-2 SAR

Three sets of synthetic aperture radar (SAR) imagery were used in this thesis to aid in the delineation of ice regime characteristics of the Parry Channel:

1. February 5, 1986 - STAR-1 imagery of Barrow Strait, Viscount Melville Sound, Prince of Wales Strait and M'Clure Strait,
2. December 9 and 10, 1986 - STAR-1 imagery of Barrow Strait, Viscount Melville Sound and Byam Martin Channel and,
3. February 14 and 15, 1987 - STAR-2 imagery of northern Baffin Bay, Lancaster Sound and Barrow Strait.

These data sets have been photographically reproduced as image mosaics and are included in this thesis in Chapter 5. These data were imaged by the STAR (Sea Ice and Terrain Assessment Radar) system developed by Intera Technologies Ltd. of Calgary, Alberta. Unlike the A.E.S. data sources mentioned in the previous sections, which are publicly collected and available, imagery provided by the STAR

system is collected on a private contract basis. These data used in this analysis were made available to the author courtesy of the Canarctic Shipping Company Ltd..

The STAR system became fully operational in early 1984 and has been used extensively for ice reconnaissance for drilling activities in the Beaufort Sea as well as in support of shipping in the eastern and western Arctic. The primary advantage of STAR-SAR compared to other ice reconnaissance systems such as SLAR or the NOAA AVHRR or visual observations is that it provides higher resolution data in all weather and lighting conditions. This higher resolution has allowed many ice features, particularly the distribution of small old ice floes, to be detected and classified. This has greatly aided the delineation of the ice regime characteristics of the Parry Channel.

The reason for the high image quality of a SAR system lies in its method of operation. By using a number of complex operations, a SAR can produce an image of substantially higher resolution than a real aperture SLAR (Ulaby, Moore, Fung 1981). For a real aperture SLAR, the image resolution in the range (across-track) direction is determined by the effective pulse length of the radar where higher range resolutions are achieved with shorter pulses. Shorter pulses require finely tuned bandwidths and high power beyond the capability of an airborne system. To alleviate this limitation, a SAR system uses complex electronic processing techniques to achieve pulse compression of longer pulses by incorporating the changing frequency of pulses with time over a given bandwidth (Ulaby, Moore, Fung 1981).

The image resolution of a real aperture SLAR in the azimuthal (along-track) direction is determined by the distance from the radar, the width of the beam and the length of the antenna. Therefore, the closer the object, the narrower the beamwidth and the longer the antenna, the higher the resolution. The processing techniques of SAR improve the resolution of an object by synthetically enlarging the apparent size of the antenna by using a wide beamwidth. Since any object

will be illuminated by a series of wide radar beams for a certain period of time as it travels across the beamwidths, the Doppler phase history can be electronically calculated. Using pulse compression techniques similar to range processing, the effective antenna length can be simulated to be many meters long, thereby greatly improving the image resolution. In addition, this technique is independent of altitude and, consequently, allows a SAR to be flown at a much higher altitude than real aperture radars (Holt, Fu 1982).

Intera Technologies Ltd. commercially operates two SAR systems, designated as STAR-1 and STAR-2. The STAR SAR systems operate in "X" band (9.1 GHz) H-H polarized from an operational altitude of 10,000 meters onboard a Cessna Conquest twin engine turbo-prop aircraft. The STAR-1 system has an azimuthal resolution of 6 meters at 25 km swath width and 12 meters at 50 km swath. The STAR-2 has an azimuthal resolution of 8 meters at 32 km wide swath and 16 meters at 64 km wide swath. The STAR systems incorporate a complex motion compensation system built into the aircraft's inertial navigation system which is connected to the radar antenna to achieve a stable image, free of excessive yaw distortion (Intera 1987). Data are recorded onboard the aircraft in an eight bit digital format on HDDR (High Density Digital Recorder) and are also available in near-real-time to surface vessels via VHF downlink system.

The STAR-1 data used for this thesis were replayed, by Intera, from the HDDR on to an EDO Corporation 590E fibre optic printer. Data were printed on to KODAK transparency film in negative format and developed on a DURR wet chemical film processor. The resultant product is a high resolution film, 23 cm wide and typically one to two metres long for each flight line produced at a scale of 1:250 000. In the case of the STAR-2 data, due to the wide-swath, these data are transcribed from the HDDR onto CCT (computer compatible tapes) at 6250 bpi (bits per inch) and replayed onto negative transparency film using an optical image recorder capable of using the wider 27 cm film to produce the image scale

of 1:250 000.

The 1:250 000 scale negative transparency film products from the STAR-1 and STAR-2 system were photographically reduced and printed in positive format at a scale of 1:1 million from which image mosaics, one for each data set, were created. These image mosaics were interpreted for ice regime characteristics and then further reduced to fit onto the 8 and one half inch by 11 inch size of this thesis. These SAR mosaics are included in Chapter 5.

Chapter 3

The Physical Environment of the Parry Channel

The formation and movement of frozen sea water is a function of the interaction of the climatic environment with the oceanographic and physiographic environment (Zubov 1943). In this chapter, the physiographic, oceanographic and climatic environment of the Parry Channel region are summarized so that the pattern of ice behaviour for the region, described in Chapter 4, may be explained and analyzed in Chapter 5.

3.1 Physiography

The Parry Channel is the collective term used to describe the waterways of Lancaster Sound, Barrow Strait, Viscount Melville Sound and M'Clure Strait. The Parry Channel represents the largest waterway in the Canadian Arctic Archipelago connecting the Arctic Ocean to Baffin Bay (Collins 1961). The Parry Channel is 800 nautical miles long, and varies in width from a minimum in central Barrow Strait of 33 nautical miles to a maximum in central Viscount Melville Sound of 94 nautical miles. The Channel is east-west oriented between 74° N and 75° N latitude and 76° W and 125° W longitude and is bordered by fifteen archipelago

islands and twelve tributary channels. The geographic layout of the Parry Channel region is illustrated in Figure 1.1 of Chapter 1.

The Canadian Arctic Archipelago, of which the Parry Channel is part, represents the flooded northern extent of the North American continental shelf bordering on the Arctic Ocean. The age of the geologic structure of the Parry Channel progresses from older to younger from east to west across the region. The eastern entrance to the Parry Channel is dominated by the northern arm of the Canadian pre-Cambrian Shield. The pre-Cambrian Shield penetrates into the Parry Channel region in the east across Baffin, Bylot, and Devon Islands and again in central Barrow Strait on Somerset Island (Bird 1967). In the east, these rocks are represented as a mountainous coastal belt running from Ellesmere Island south along the east coast of Baffin Island. These mountains are alpine in character with sharp peaks and ridges with discontinuous ice caps. Bylot Island contains some of the highest topography in the region with peaks exceeding 1800 metres. The eastern end of Devon Island is dominated by a large continuous ice cap with a surveyed altitude in excess of 1800 metres (Dunbar, Greenaway 1956).

The majority of the rocks of the central and western portion of the Parry Channel are Cambrian sedimentary rocks. The area along the south side of the Parry Channel consists primarily of flat lying Paleozoic sediments, interrupted in central Barrow Strait by a pre-Cambrian fault ridge. Extensive limestone and sandstone deposits occur throughout the region and form numerous steep sided cliffs in the east, particularly along the south shore of Devon Island and the north shore of Baffin Island.

The youngest rocks in the region are found along the western perimeter of the Queen Elizabeth Islands in the Arctic Coastal Plain. These rocks are flat and low lying compared to the limestone cliffs and large pre-Cambrian mountain chain typical of the eastern entrance to the Parry Channel.

In the east, elevations of 700 to 1500 metres predominate along the coasts of

Devon, Baffin and Bylot Islands on the shores of Lancaster Sound. The elevations of the central and western portions of the region are much lower than those to the east with elevations averaging between 100 to 250 metres.

The significance of the physiography of the Parry Channel as it affects both the sea ice environment and marine navigation is three-fold:

1. The varied geology of the region provides important mineral and oil deposits upon which resource development and exploitation requiring marine transportation is predicated.
2. The high relief of the eastern portion of the region modifies the prevailing winds that contribute to ice movement (Frazer 1983). In addition, the steep coastal cliffs enhance the capture of solar radiation in the region.
3. The low relief of the central and western portion of the region results in little topographical modification of the prevailing winds (Frazer 1983).

3.2 Hydrographic Environment

The waterways of the Canadian Arctic Archipelago serve as connective passages for the flow of Arctic Ocean water into Baffin Bay and the Atlantic Ocean. The total cross-sectional area of the straits of the Archipelago joining the Arctic Ocean to Baffin Bay is equivalent to a waterway 120 km wide and 340 metres deep. This area represents six percent of the total cross-sectional area through which there may be an exchange of water between the Arctic Ocean and the Atlantic and Pacific Oceans (Collins 1962). The origin and movement of the sea water which forms the ice environment of the Parry Channel will be described here.

3.2.1 Bathymetry

The bathymetry of the Parry Channel varies from a maximum of greater than 800 metres in eastern Lancaster Sound to a minimum threshold depth of 150 metres in central Barrow Strait. The bathymetry of the Parry Channel is shown in Figure 3.1. The continental shelf drops off sharply in the eastern Arctic in northwestern Baffin Bay. A deep water trough exists in central and eastern Lancaster Sound reaching a maximum depth of over 800 metres north of Bylot Island. It is generally thought that this trough is the result of glacial deepening during a period when the land elevation was much higher above sea level than at present (Collins 1962). This trough becomes shallower to the west and has its terminus in northern Prince Regent Inlet.

Water depths decrease gradually in eastern Barrow Strait from 300 metres to the shallowest threshold depth of under 150 metres in central Barrow Strait near Lowther Island. A large shallow water bank occurs in western Barrow Strait south of Bathurst Island with depths ranging from 50 metres to as little as 10 metres closer to shore. A shallow water bank, known as the Keen Bank, occurs in south-central Austin Channel. Depths increase to the west in Viscount Melville Sound reaching a maximum depth of 500 metres in a basin in central and western Viscount Melville Sound. Depths remain relatively uniform at 400 to 500 metres through M'Clure Strait into the broad continental shelf of the Beaufort Sea. There are no gullies or canyons present in the continental shelf bordering the western end of the Archipelago. This is likely due to the lack of any glacial deepening in the region since the western-most extent of the Arctic Islands escaped glaciation (Bird 1967).

3.2.2 Water Masses and Currents

The Parry Channel represents the major waterway of the Arctic Archipelago separating waters of Arctic Ocean origin to the west from those of Arctic and Atlantic

Figure '3.1: Bathymetry of the Parry Channel - depth in metres.
(Source: Canadian Hydrographic Service - nautical charts)

origins to the east. There is a general flow of waters from the Arctic Ocean eastward to Baffin Bay through the Archipelago. Due to the limiting bathymetry of 150 metres in central Barrow Strait, only the upper portion of the Arctic Ocean water column is transported eastward into Lancaster Sound and Baffin Bay (Collins 1962). Hence, there is a complex interaction of waters of both Arctic and Atlantic Ocean origin in the eastern Parry Channel.

Water Masses

The hydrographic profile of the Arctic Ocean has three layers. The upper layer, which extends from the surface to approximately 200 metres, is characteristic of Arctic Ocean water consisting of low temperature (-1.9 to 0°C) and low salinities of $32^{\circ}/\text{oo}$ (Collins 1962). This layer has been given the name "cold pycnocline" by some investigators (Melling *et al.* 1984). A sharp thermocline separates the Arctic Ocean layer from a layer of warmer temperature and higher salinity which extends from 200 meters to 800 metres in depth. This deep layer has been identified as having its origins from the Atlantic Ocean and is known as the Atlantic layer. Temperatures in this region vary between 0.4 to 5.0°C and this layer has higher salinities typical of waters from the Atlantic Ocean of 33.3 to $34.7^{\circ}/\text{oo}$ (Melling *et al.* 1984). The origin of the Atlantic layer occurs off the north coast of Norway where the north flowing Gulf Stream of the Atlantic Ocean branches off in the Barents Sea and again along the west coast of Spitsbergen where it submerges to continue as a sub-surface current into the Arctic Ocean (Dunbar and Greenaway 1956). The lower layer of the Arctic Ocean, extending from 800 meters to the sea bottom, is characterized as having lower temperature but with salinities similar to the Atlantic layer.

The waters of the western portion of the Parry Channel have their origins in the Arctic Ocean to the west. It has been found that surface water temperature and salinities increase slightly as the Arctic Ocean waters slowly move eastward

through M'Clure Strait and Viscount Melville Sound. Oceanographic studies have found that the coldest waters enter the Parry Channel along the south side of M'Clure Strait. These investigations have also found that the warmest waters of the western Parry Channel occur along the north side of the Channel, being 0.1 to 0.2°C warmer than those that enter the Channel from the Beaufort Sea (Melling *et al.* 1984). This warmer surface water corresponds to a cooler underlying Atlantic layer in the Parry Channel. It has been hypothesized that as the Arctic Ocean water moves into the shallow water of the Archipelago, a heat transfer and mixing of the Atlantic layer into the colder overlying Arctic Ocean layer occurs (Melling *et al.* 1984). This finding is supported by nutrient studies which have found small amounts of silicate and phosphate concentrations in central Viscount Melville Sound typical of waters of Atlantic and Pacific Ocean origins (Jones and Cootes 1980). It is speculated by Melling *et al.* (1984) that the thinner ice development in recurrent polynya and thin ice areas in Penny Strait and northern Viscount Melville Sound are the result of heat transfer from the Atlantic layer into the upper Arctic layer.

As the Arctic Ocean waters move eastward into Barrow Strait only the upper 150 meters of the now modified Arctic Ocean cold pycnocline is allowed to continue eastward into eastern Barrow Strait and Lancaster Sound. This limitation is due to the shallow 150 meters threshold depth of central Barrow Strait which blocks the further eastward movement of the deeper Atlantic layer (Birch *et al.* 1983).

Atlantic Ocean waters penetrate into the eastern Canadian Arctic through Davis Strait and Baffin Bay as part of the north flowing west Greenland Current. The relatively cold, low salinity Arctic Ocean waters enter the eastern portion of the Parry Channel and northern Baffin Bay from Barrow Strait to the west, Norwegian Bay and Jones Sound from the north-west and Nares Strait to the north. This results in the cold Arctic Ocean layer dominating the upper 200 meters with the warmer, more saline Atlantic layer occurring below. The current velocities and

flow characteristics of the water masses of the eastern Parry Channel and northern Baffin Bay are much more dynamic than those to the west (Collins 1962). This results in a greater interaction of the lower Atlantic layer into the upper Arctic layer and produces surface waters in northern Baffin Bay and Lancaster Sound with higher temperatures and salinities than further west in the Parry Channel (Collins 1962). The western-most penetration of Atlantic waters from Baffin Bay into the Parry Channel has been found to occur as far west as central Barrow Strait (Collins 1962), although the normal intrusion is thought to be limited to east of 86° W (Fissel *et al.* 1981).

The highest surface water temperatures in northern Baffin Bay occur east of Philpots Island where temperatures reach in excess of 5°C by the late summer (Maxwell 1982). This area occurs above the edge of the continental slope. This shallowing continental slope likely forces the deep Atlantic Ocean waters upwards towards the surface creating higher surface water temperatures and salinities in northern Baffin Bay. This region forms the location of the important North Water Polynya (Smith and Rigby 1981) which exerts an important influence on the ice distribution (Markham 1981) and climate (Maxwell 1980) in the region.

Currents

The circulation of the Arctic Ocean is in a slow clockwise gyre with the centre located near 80° N 100° W (Maxwell 1982). This flow produces a north-east to south-west flow across the north-western perimeter of the Archipelago. The current moves slowly, in the order of 1 nautical mile per day in summer and 0.5 nautical miles per day in winter (Collins 1962). A weak southward movement of Arctic Ocean waters flow through Nares Strait between Ellesmere Island and Greenland, and has been measured to flow at a rate of 10 nautical miles per day (Collins 1962). The source of these waters is thought to be from the trans-polar current from the Eurasian Basin of the Arctic Ocean with little influence from

the Canadian Basin to the west, although this is disputed by some investigators (Jones and Cootes 1980).

The Arctic Ocean waters enter the Arctic Islands through the many passages between the islands with major incursions occurring in the Prince Gustaf Adolf Sea north of the Sverdrup Basin, and M'Clure Strait at the western entrance to the Parry Channel. The west to east drift rate of water is slow through the channels, with many counter currents and eddies occurring, particularly in the eastern portion of the Parry Channel (Leblond 1980). Figure 3.2 shows the pattern of surface water current movement in the Parry Channel. The pattern of surface water movement has been found, in this thesis, to have a strong influence of the patterns of ice distribution for the Parry Channel and, ultimately, the definition of the ice regimes of the region. In the remainder of this section, these surface water currents will be described.

A 0.5 to 0.8 nautical miles per day current moves eastward through M'Clure Strait. This weak current has been recognized to have a strong wind driven (Melling *et al.* 1984) and tidal component (Canadian Hydrographic Service 1981). A weak flowing current, thought to be intermittent and tidal, has been recorded flowing westward along the north side of the Strait near Cape Providence (Canadian Hydrographic Service 1981).

A moderate counter-current in Prince of Wales Strait has been recorded. These currents consist of a 6 to 12 nautical mile per day current flowing south along the west side of the Strait from Viscount Melville Sound and an opposite current of equal strength flowing north along the east side from Amundsen Gulf (Canadian Hydrographic Service 1981).

The weak eastward flow from the Arctic Ocean continues into Viscount Melville Sound where no discernible current in any direction is identified (Canadian Hydrographic Service 1981). The current patterns of the western portion of the Parry Channel are poorly known (Birch *et al.* 1983) but are considered so weak as to

Figure 3.2: Current patterns for the Parry Channel.
Velocities in nautical miles per day (Sources: Numerous - see text)

have a limited effect on the movement of ice in the region (Verrall et al. 1974).

A moderate current, measured to vary between 5 and 10 nautical miles per day, flows south through Byam Martin Channel into Byam and Austin Channels (Melling et al. 1984). This current flows southward through Byam Channel and continues westward along the south shore of Melville Island before turning cross channel to the south then eastward in Viscount Melville Sound. Similarly, the current flowing southward through Austin Channel also is deflected to the right around Byam Martin Island, by Coriolis forces, before turning eastward into western Barrow Strait.

A current of 5 to 10 nautical miles per day flows southward through Penny Strait between Bathurst and Devon Islands from the Sverdrup Basin (Melling et al. 1984). This current flows into the Queen's Channel and subsequently into McDougall Sound as well as Wellington Channel.

The current patterns of central and eastern Barrow Strait are complex as the weak eastward current of Viscount Melville Sound mixes with south bound currents of McDougall Sound, Wellington Channel and the north bound current of Peel Sound. The currents flowing south-west out of McDougall Sound meet the weak eastward flowing current of western Barrow Strait at Lowther Island. This meeting produces a south-eastward flow toward Peel Sound where counter currents of southward flow along the west side of the Sound are matched with a north flow on the eastern side. Current velocities have been measured to be relatively weak to moderate, not exceeding 14 nautical miles per day in the area (Fissel and Marko 1978). A westward flowing current south of Griffith Island in northern Barrow Strait has been identified (Fissel and Marko 1978) and it eventually flows northward along the west shore of Cornwallis Island in McDougall Sound, and has been measured at 11 to 14 nautical miles per day (Canadian Hydrographic Service 1985). The result of this current pattern is a weak counter-clockwise flow in central Barrow Strait (Fissel and Marko 1978).

A moderate current of 20 nautical miles per day flows southward out of Wellington Channel (Canadian Hydrographic Service 1981). This current follows the east coast of Cornwallis Island slightly to the west, before moving diagonally southeastward across eastern Barrow Strait. This current meets with the eastward flowing current from central Barrow Strait along the north coast of Somerset Island. This current in eastern Barrow Strait has been measured to extend from the Somerset Island coastline 17 nautical miles north into the central portion of the Strait. The velocity of the current has been found to increase as it moves eastward toward Prince Leopold Island (Fissel and Marko 1978).

In western Lancaster Sound, east of Prince Leopold Island, a gyral current occurs. This current is made up of an intense current flowing east past Prince Leopold Island from Barrow Strait which flows southward along the western side of Prince Regent Inlet at measured velocities exceeding 20 nautical miles per day (Fissel *et al.* 1981). A weaker counter current flows north along the east coast of Prince Regent Inlet then eastward along southern Lancaster Sound. This current, combined with an intermittent weak west flowing current occasionally found along the north side of western Lancaster Sound (Collins 1962) creates a counter-clockwise flowing gyre in western Lancaster Sound. Additional temporary gyres occur north of Admiralty Inlet as the east flowing current from western Lancaster Sound interacts with the strong intrusive westward flowing current from Baffin Bay.

A strong current flows south eastward out of Jones Sound through Lady Ann Strait. This current follows the coastline of Philpots Island and is centered 8 to 10 nautical miles east of shore and reaches flow rates of 20 to 30 nautical miles per day. This current continues to follow the coastline of Philpots and Devon Islands westward into Lancaster Sound eventually turning south-westward then westward into north-eastern Lancaster Sound. The flow of this current is most intense off Cape Sherard, Devon Island, reaching velocities of up to 50 nautical miles per

day (Fissel et al. 1981). This current is the dominant current of eastern Lancaster Sound. This intrusive current follows the Devon Island coastline and gradually moves cross-channel to the south to join the eastward flowing current found on the south side of Lancaster Sound and subsequently exits the Sound north of Bylot Island. The majority of the current flows cross-channel between 20 to 40 nautical miles west of the eastern entrance of Lancaster Sound between Cape Warrender and Croker Bay and south to Navy Board Inlet. It is rare for any part of this current to be encountered west of 88° W. This current averages 36 nautical miles per day but can be highly variable (Fissel et al. 1981, Stepney 1977).

As the intrusive current moves westward into and across Lancaster Sound, many counter currents and gyres are developed in the central portion of the Sound. The most significant feature of this pattern is the central disordered zone located in central Lancaster Sound north of Bylot Island. This area is characterized by a weak disordered flow with rates of movement from 0 to 5 nautical miles per day (LeBlond 1980).

The outflow of the current along the south side of Lancaster Sound averages 30 nautical miles per day and becomes detached from the south shore near Cape Liverpool, Bylot Island. This leaves a large disordered zone east of Bylot Island in Baffin Bay where intermittent eddies and counter current are frequently encountered (Fissel et al. 1981).

It has been noted by several investigators (Fissel et al. 1981, Collins 1962) that surface water current velocities have been measured or are speculated to be lower in the late fall and winter months than the summer period in the Canadian Arctic. However, very few oceanographic investigations have been undertaken in the Canadian Arctic outside of the August or September period.

Tides

The movement of tidal energies through a water body has been found to have a significant effect on the timing and extent of both break-up as well as freeze-up (Zubov 1943). During the freeze-up period, tidal energies may delay consolidation by mixing the water column thereby providing warmer water to the surface. In addition, the ebb and flow of the tide introduces movement to an ice cover thereby delaying consolidation. In the spring break-up period, tidal energies weaken the ice cover through the creation of shore fractures (Zubov 1943). The variation in tidal energies from the relatively high energies in the eastern Parry Channel to low energies in the western segment may be an important variable in the behavior of the ice cover, and the creation of ice regimes, in the Parry Channel.

The tides in the Canadian high Arctic Islands are primarily of Atlantic Ocean origin. Atlantic Ocean tides are semi-diurnal with a period of oscillation of 12.6 hours producing two high tides and two low tides each lunar day (28.98 hours) (Forrester 1983). Tidal energy is forced into Baffin Bay from the Labrador Sea with Baffin Bay acting as an amphidromic basin for the tidal waves propagating through Davis Strait. Due to Coriolis force, the tidal waves propagate cyclonically around Baffin Bay in an anti-clockwise fashion with the amphidromic point occurring in west central Baffin Bay (Greisman *et al.* 1986). The tide propagates northward along the west coast of Greenland turning westward into Smith, Jones, and Lancaster Sounds.

In the Parry Channel, the tidal wave energy propagates westward through Lancaster Sound dividing southward into Prince Regent Inlet and westward into Barrow Strait and subsequently into Viscount Melville Sound. Local tidal current studies in central Barrow Strait have recorded the movement of tidal energies westward through Barrow Strait as well as a significant movement northward into Wellington Channel (Greisman, Lake 1978). The northward movement of the tide has been recorded strong enough to stop, temporarily, the southward Wellington

Channel current during the flood tide (Canadian Hydrographic Service 1981).

The tidal wave propagates northward into northern Wellington Channel and follows the north coast of Cornwallis Island through Maury Channel into the Queen's Channel then southward into Crozier and Pullen Strait into northern McDougall Sound. It has been speculated that tidal forces are a contributing factor to the formation of the Queen's Channel polynya (Markham 1981). This tidal cause of this polynya is quite possible since, as a tidal wave propagates into shallow water, shoaling of the tidal energy occurs which results in a decrease of wave speed and a corresponding increase in tidal energy with the result that an increase in tidal current and height occurs (Forrester 1983). It has been reported that tidal heights are amplified in several areas near shore areas in the eastern Parry Channel, particularly in Lancaster Sound (Fissel *et al.* 1981).

Tidal energy moving through Barrow Strait continues into Viscount Melville Sound as well as north into McDougall Sound. The movement of tidal energies into McDougall Sound, both from the north and south, create complex tidal currents, often from opposing directions (Greisman, Lake 1978).

Tidal energies entering Viscount Melville Sound from Barrow Strait propagate southward down M'Clintock Channel and counter clockwise around Prince of Wales Island then subsequently northward into Peel Sound (Greisman *et al.* 1986).

Tidal energies diminish as they move east to west through the Parry Channel. Tidal ranges diminish from 2 metres at the entrance to Lancaster Sound to less than 0.5 metres in Viscount Melville Sound (Maxwell 1982, Canadian Hydrographic Service 1981). However, tidal energies in near shore areas, particularly Winter Harbour, Melville Island, can achieve spring tides as high as 1.5 metres (Canadian Hydrographic Service 1981). Analysis of tidal data has indicated that the presence or absence of an ice cover has no appreciable effect on the timing or range of tides in the Parry Channel (Godin 1980a, 1980b).

The tides in the Arctic Ocean are low, averaging under 1.0 metre in the Beau-

fort Sea. The tidal currents that enter McClure Strait from the Arctic Ocean are very weak resulting in a tide of less than 0.5 metres (Canadian Hydrographic Service 1981). The tidal forces for the Arctic Ocean are poorly understood (Godin 1980c).

The propagation of the Atlantic tidal wave into Nares Strait reaches its maximum amplitude in the Kane Basin. The movement of the tide into the shallower waters of Nares Strait creates a shoaling and channeling of the tidal energy such that the strongest tidal current recorded in the Canadian Arctic occurs in the Kennedy Channel, where it reaches velocities of 25 nautical miles per day. Due to the south flowing current through Nares Strait, a standing tidal wave of up to 1.0 metre in height has been observed in the Kane Basin (Greisman *et al.* 1986). The Atlantic tidal energy continues northward through Nares Strait into the Arctic Ocean. Tidal measurements in Nares Strait have shown a possible southward propagation of tidal energy from the Arctic Ocean south into the north end of the Robeson Channel (Greisman *et al.* 1986).

The tides of the Parry Channel are classified as mixed, mainly semi-diurnal (MSD) by the Canadian Hydrographic Service. This implies "two high water and two low water tides each lunar day, but with marked inequalities in height and irregularities in spacing" (Forrester 1983, p. 35). A small area along the south shore of Melville Island in Viscount Melville Sound has been classified as semi-diurnal (SD) which implies "two nearly equal high waters and two nearly equal low water tide approximately uniformly spread over each lunar day" (Forrester 1983, p. 35).

3.3 Climatic Environment

The primary physical factors controlling the climate of the Parry Channel region are latitude, the distribution of land and water and the behavior of weather systems

moving into the region (Dunbar and Greenaway 1956, Maxwell 1980, Frazer 1983). Due to the high latitude of the Parry Channel, there is a marked variation in the amount of solar radiation received in the region over the year. The Parry Channel lies along the 74° N parallel. This latitude results in twenty-four hour a day sunlight between the last week of April and the second week of August with the sun below the horizon twenty-four hours a day from the first week of November to the last week of January. The lack of solar radiation during the mid-winter months results in a long period of continual radiative heat loss to the atmosphere from the ocean and land surfaces. In addition, the low sun elevation, of 49° at maximum elevation for the Parry Channel at the summer solstice (compared to 69° for southern Ontario) and high albedo from snow cover on land and sea ice further reduce the energy potential of solar radiation in the high Arctic (Maxwell 1980). The influence of topography, particularly the south facing steep slopes of the eastern Arctic, is to increase the capture of solar radiation and to modify the flow of the prevailing winds in local areas. However, the factor which influences the climate of the high Arctic region the most is the persistence of a perennial high pressure anti-cyclonic system over the Arctic Ocean northwest of the Parry Channel and the perennial low pressure cyclonic system present in southern Davis Strait (Dunbar and Greenaway 1956, Bird 1967, Maxwell 1980, Frazer 1983). The movement of air masses and weather systems between these two features has a profound effect on the winds, temperatures and precipitation received over the Parry Channel region. These patterns will be described in the following sections.

3.3.1 Air Masses and Wind

A low pressure area exists in Baffin Bay in all seasons (Frazer 1983). This area results from warmer temperatures of the north Atlantic Ocean relative to cool temperatures of the Greenland ice cap and the Arctic Ocean. A high pressure system exists over the Arctic Ocean northwest of the Parry Channel in all seasons.

This area results from the cold temperatures of the Arctic basin relative to warmer air masses of the north Pacific and north Atlantic Oceans. The pressure gradient between these two air masses is strongest in mid-winter (averaging 102.2 KPa over the Arctic Ocean and 100.0 KPa over Davis Strait in January) and weakest in mid-summer (averaging 101.2 over the Arctic Ocean and 101.0 KPa over Davis Strait) producing a strong and persistent northwest to southeast wind flow in winter and a weak and variable easterly and south-easterly flow in the mid-summer over the Parry Channel (Maxwell 1980).

During winter months, the Arctic Ocean and waterways of the western portion of the Arctic Archipelago are primarily solid pack ice. This produces a large sea surface area with radiative characteristics similar to land masses (Dunbar and Greenaway 1956). Consequently, the air mass produced over the Arctic Ocean is dry and very cold, intensifying as winter progresses as a result of the large radiative heat loss due to the total lack of incoming solar radiation. This air mass is classified as Continental Arctic (cA) (Maxwell 1980).

The north Atlantic Ocean is dominated by an air mass classified as Maritime Arctic (mA) during the winter months (Maxwell 1980). This air mass is characteristically maritime with high moisture content and contains the highest temperatures to be found in the Arctic region during winter (Dunbar and Greenaway 1956).

During winter months, the cA air mass from the Arctic Ocean dominates the Parry Channel producing cold, dry and clear conditions with a dominant northwest wind flow from late November to early April. Resolute Bay, located on the south coast of Cornwallis Island on the north shore of central Barrow Strait, has recorded average winds of 10 to 12 knots during the period with relative humidity of 68 percent, average temperatures of -30°C and little to no cloud cover. Mould Bay, located in the western Arctic on Prince Patrick Island near the north shore of M'Clure Strait, records similar weather conditions during the winter period

(Canadian Hydrographic Service 1982).

Temperatures begin to increase in the high Arctic by mid-April with the onset of twenty-four hour a day solar radiation. With the temperature increase, there is an expansion of the mA air mass from Baffin Bay further north and a corresponding contraction of the cA air mass north-westward into the Arctic Ocean in the spring. The pressure gradient between the maritime air mass of Baffin Bay and the continental air mass of the Arctic Ocean declines such that it is nearly non-existent by mid-summer (Stepney 1977). This air mass expansion results in the mA air mass dominating the Parry Channel region during the June to September period, bringing with it a warm, moist air mass with high cloud cover and variable wind flow. During summer the climate of the high Arctic is affected by numerous frontal systems moving into the Arctic Islands, a phenomenon much less common in the winter (Frazer 1983).

The primary storm track into the Parry Channel region is northwest from Davis Strait through Baffin Bay to the entrance of Lancaster Sound. Two secondary storm tracks also occur: one parallel to the Parry Channel from Alaska to Greenland as well as a storm track from Hudson Bay into the eastern Arctic. The Baffin Bay primary corridor is active throughout the year with the secondary tracks active in June to November (Frazer 1983, Maxwell 1980). As storms track northward into the high Arctic, particularly in Baffin Bay, they begin to fill and occlude in northern Baffin Bay due to the injection of colder air from the Greenland ice cap and colder sea conditions (Frazer 1983). Due to the generally shallow cyclonic systems that develop over the high Arctic during the summer months, it is not uncommon for weather systems to become blocked and remain stationary for long periods, often the better part of the spring and summer season. This phenomenon often results in above or below average temperatures being experienced for an entire summer season in the high Arctic (Bird 1967).

Weather conditions for Resolute Bay for June to September are characterized

by near freezing temperatures, averaging above freezing for July and August, with relative humidity over 85 percent and extensive cloud cover. Almost fifty percent of the days in August report fog and over sixty percent of the precipitation for the year falls in the months of June to September. Winds are variable with an equal occurrence of winds from the south, south-east and north-west (Canadian Hydrographic Service 1982).

As the fall season develops, in late August and September, the cA airmass over the Arctic Ocean begins to expand into the Queen Elizabeth Islands and the mA air mass contracts. The intensity of the pressure gradient between the Arctic Ocean high pressure area and the low pressure area over southern Baffin Bay begins to intensify. This interaction of the dry, cold continental air of the Arctic Ocean with the warm, moist maritime air brings the most active period for cyclonic disturbances for the Parry Channel in September to early November (Frazer 1981, Maxwell 1980). Winds begin to intensify from the north-west as temperatures plunge below 0°C by mid-August in the western portion of the Parry Channel and mid-September for Lancaster Sound. Clearer, colder conditions typical of winter become well established by mid to late November over the Parry Channel (Bird 1967, Frazier 1983).

3.3.2 Temperatures

The annual temperature variation in the Parry Channel region is broad ranging from average winter temperatures of -40 to -50°C in mid-February to as high as 10°C by late July. There is a distinct regional variation in average temperatures across the Parry Channel with the warmest temperatures occurring in eastern Lancaster Sound and progressing to the coldest temperatures in western Viscount Melville Sound and M'Clure Strait. The average annual temperature at Pond Inlet, located near the entrance to Lancaster Sound, is -15.0°C while at Resolute Bay, located in central Barrow Strait, it is -16.6 and at Mould Bay, Prince Patrick

Island, located near M'Clure Strait, it is -17.8°C (Canadian Hydrographic Service 1982). The proximity of the eastern Parry Channel to the moderating effect of warmer water masses (see section 3.2) and air masses of Baffin Bay relative to the colder air and water masses of the Arctic Ocean to the west is the primary reason for the temperature variation (Markham 1981, Maxwell 1980).

February is the coldest month for the Parry Channel with monthly temperatures averaging below -35°C for the entire region. Average temperatures rise gradually to above -20°C in April with average daily temperatures above freezing being experienced in the eastern region by the last week of May, the first week of June in the central Parry Channel and late June in the west. This increase in temperature is in response to the return of twenty-four hour a day solar radiation and the expansion of the mA air mass from Baffin Bay into the region (Fraser 1983).

Daily average temperatures below freezing return to the Parry Channel by mid-August in the west, late August in central Barrow Strait and early September in Lancaster Sound. The return of freezing temperatures results from the reduction of solar radiation and the expansion of the cA air mass into the region from the Arctic Ocean. The temperature fall is gradual in September and early October as extensive open water areas in the Parry Channel region serve to modify the cold air masses. However, by early November, ice growth has become sufficiently advanced that very cold temperatures typical of the winter period return to the Parry Channel.

The period when temperatures are near or above freezing, from late May to early September, is a critical period for the ice regimes of the Parry Channel (Hotzel, Noble 1979). Small variations in air temperatures of only a few degrees above or below normal will have a significant effect on the ice of the region. The accumulation of melting degree days (MDD) (a degree day being one unit for 1.0°C above 0°C for each day) is very low for the high Arctic so above or below

average temperatures for two or more weeks could significantly alter total accumulated MDD. Such an occurrence would create a much above average break-up year or much below average year. Therefore, the most important element of the temperature regime for the Parry Channel is the temperature fluctuation that occurs above or below normal during the brief Arctic spring and summer.

3.3.3 Precipitation

Average annual precipitation in the Parry Channel is highest at the entrance to Lancaster Sound and lowest in western M'Clure Strait. Pond Inlet receives an average annual accumulation of 181.8 mm of precipitation while Resolute, located in the central Parry Channel, receives 131.4 mm and Mould Bay, located near M'Clure Strait to the west, receives 93.1 mm of precipitation (Canadian Hydrographic Service 1982).

Precipitation occurs primarily in summer and fall when the mA air mass provides moisture to the Arctic region. During the winter months, when cold, dry cA air mass dominates, precipitation is infrequent occurring usually only when low pressure systems penetrate the region, a rare event during the winter months (Maxwell 1980).

Most precipitation in the Parry Channel occurs as snow which is significant to ice development due to snow's insulating effect. In addition, snow melt during the spring provides a fresh water leach of the warming ice surface which facilitates brine removal from first year ice (Zubov 1943). This effect is presumed to be greater in the eastern Parry Channel than the west due to the higher precipitation in the area. This higher precipitation value in the eastern Parry Channel is likely due to the proximity of the moist mA air mass of Baffin Bay and the frequent cyclonic system which move into and occlude in northern Baffin Bay (Fraser 1983). In addition, the moisture provided by the North Water Polynya adds to the precipitation potential and is thought to be a contributing agent to the persistence of the Devon Island ice

cap, which receives the highest annual precipitation in the Canadian high Arctic at over 300 mm per year (Dunbar and Greenaway 1956).

3.4 Summary - Physical Environment Characteristics

As described by Zubov (1943) sea ice will grow and move in response to variables in the atmospheric and oceanographic environment. Therefore, it follows that regional variations in the physical environment will cause regional variations in the sea ice environment. The regional variations in sea ice characteristics will be used to aid in the definition of the ice regimes of the Parry Channel. In this chapter, the regional variations in the oceanographic and atmospheric environment of the Parry Channel have been described. The major physical environment characteristics which vary across the Parry Channel are:

1. Physiography

The high relief of Lancaster Sound contrasts sharply with the flat lying topography of the central and western Parry Channel. Consequently, the topographic modification of surface winds and solar radiation capture will vary between Lancaster Sound and the remainder of the Parry Channel region which may in turn influence ice growth and movement.

2. Water Masses

Regional variation in interaction of the warm Atlantic layer with the overlying colder and less saline Arctic Ocean layer is likely a very important physical parameter which causes regional variation in the sea ice environment in the Parry Channel. For example, areas where the Atlantic layer intrudes and mixes with the overlying Arctic Ocean layer will have warmer

and more saline water which may inhibit ice growth (i.e., the North Water polynya and possibly the first year ice area along the north side of Viscount Melville Sound south of Melville Island). It is speculated in this thesis that the predominance of the Atlantic Ocean water mass in Lancaster Sound and Barrow Strait and the predominance of the Arctic Ocean water mass in Viscount Melville Sound and M'Clure Strait are undoubtedly the major factors causing the marked variations in ice regime characteristics between these water bodies.

3. Currents

There are marked regional variations in the surface water currents in the Parry Channel. Moderate to strong currents predominate in Lancaster Sound and Barrow Strait while weak to non-existent currents predominate in Viscount Melville Sound and M'Clure Strait. The occurrence of counter-currents, gyres and mixing areas are important characteristics in delineating the numerous ice sub-regimes in the Parry Channel.

4. Tides

The contrast between the strong tidal energies of the Atlantic Ocean and the very weak tides of the Arctic Ocean across the Parry Channel is also speculated in this thesis to be an important factor in causing the regional variations in the ice characteristics of the Parry Channel. The strong penetration of Atlantic tides into central Barrow Strait may have an important influence on break-up and freeze-up patterns which, in turn, would affect ice regime boundary selection.

5. Air Masses and Climate

The proximity of the eastern Parry Channel to the warm moist Maritime air mass of Baffin Bay and the Atlantic Ocean compared to the western Parry

Channel's proximity to the cold dry Arctic Ocean air mass is also likely an important cause for the variation in ice characteristics across the Parry Channel.

Chapter 4

Historical Review of Ice Conditions 1974-1986 for the Parry Channel

The purpose of this chapter is to identify and summarize the spatial and temporal patterns of ice break-up, movement and freeze-up for the Parry and adjacent channels. These patterns were determined from NOAA satellite imagery and A.E.S. Ice Charts covering the period of January 1974 to December 1986. This summary is pivotal to achieving the objective of this thesis in that these patterns form the framework from which the ice regime characteristics for the Parry Channel are identified. It is not the intent of this chapter to explain the reasons for the patterns but, rather, to describe in detail the patterns that occur. The relationships of major oceanographic and atmospheric components, identified in Chapter 3, to the ice behavior patterns, identified in this chapter, are analyzed in Chapter 5 to identify the ice regime characteristics of the Parry Channel.

This chapter is divided into four sections describing the following ice behavior patterns for the Parry Channel:

1. Break-up patterns (Section 4.1).
2. Summer and early fall ice reduction and movement (Section 4.2).
3. Freeze-up and consolidation patterns (Section 4.3).

4. Old ice sources and movement (Section 4.4).

4.1 Break-up Patterns

4.1.1 Early Spring Limits of Consolidation

The pattern of break-up in the Parry Channel region follows a regular sequence spanning from late April to mid-August. The early stages of fracture and clearing for the Parry Channel are influenced by the extent of consolidation which occurred the previous winter. The portion of the Parry Channel west of Russell Island, which includes western Barrow Strait, Viscount Melville Sound, M'Clure Strait and Prince of Wales Strait consolidated every winter during the thirteen years of this study. However, the degree of consolidation which occurs in the eastern portion of the Parry Channel, which includes central and eastern Barrow Strait and Lancaster Sound, has varied widely over the study period.

The variability of extent of consolidation in the early spring period in the eastern portion of the Parry Channel over the past twenty-two years is well described in the literature (Lapp 1984, Hotzel, Noble 1979). All recorded variations of consolidation observed over the past twenty-two years had also occurred during the thirteen year period of this study. However, the variation in the degree of consolidation in the western portion of the Parry Channel is not well described in the literature. The locations of eastern and western known limits and variation of consolidation are illustrated in Figure 4.1. The years in which these locations have occurred over the past twenty-two years for the eastern Parry Channel are shown in Table 4.1. The locations of the consolidated ice edge for the western Parry Channel identified in the thirteen years of this study are shown in Table 4.2.

There were six locations where the early spring consolidated ice edge has oc-

Figure 4.1: Locations of consolidated winter ice edges in the Parry Channel.
See Table 4.1 and 4.2 for legend.

Table 4.1
Early Spring Consolidated Ice Edge Locations
Barrow Strait and Lancaster Sound
1964 - 1986

Location	Years	Percent of 22 year period
A) Resolute to Griffith Island to Lowther Island to Russell Island.	1986	4
B) Resolute to Griffith Island to Somerset Island	1964 1969 1974 1976	18
C) Devon Island to Prince Leopold Island to Somerset Island.	1965 1973 1966 1975 1967 1977 1968 1980 1971 1981 1972 1985	54
D) Devon Island to central Brodeur Peninsula, Baffin Island.	1982	4
E) Devon Island to Cape Charles Yorke, Baffin Island	1970 1984	9
F) Devon Island to Bylot Island east of Navy Board Inlet	1978 1979 1983	13

(Sources: This study and Lapp 1984, Hotzel and Noble 1979)

Table 4.2
Early Spring Consolidated Ice Edge Locations

M'Clure Strait 1974 - 1986		
Location	Years	Percent of 13 year period
G) Cape M'Clure, Banks Island to Prince Patrick Island across central M'Clure Strait.	1976 1982 1977 1979	31
H) Cape Prince Alfred, Banks Island to Prince Patrick Island in western M'Clure Strait.	1974 1983 1975 1985 1980 1986	46
I) Cape Prince Alfred, Banks Island to Prince Patrick Island.	1978 1984 1981	23
Amundsen Gulf 1974 - 1986		
J) Eastern Amundsen Gulf	1978 1981	15
K) Western Amundsen Gulf from Cape Lambton, Banks Island to Cape Parry N.W.T.	1974 1982 1975 1983 1976 1984 1977 1985 1979 1986 1980	85

curred in the eastern Parry Channel between 1964 and 1986. They were:

1. From Resolute Bay to Griffith Island to Lowther Island to Russell Island. This formed only once in the past twenty-two years and represents the minimum extent of consolidation recorded (spring 1986).
2. From Resolute to Griffith Island to Somerset Island across central Barrow Strait. This has formed in four of the past twenty two years (spring 1964, 1969, 1974, 1976).
3. From eastern Somerset Island to Prince Leopold Island to Devon Island across eastern Barrow Strait at the western entrance to Lancaster Sound. This is the median location, occurring in twelve of the past twenty-two years (spring 1965, 1966, 1967, 1968, 1971, 1972, 1973, 1975, 1980, 1981, 1985).
4. From Brodeur Peninsula, Baffin Island, to central Devon Island across western Lancaster Sound. This is a rare location occurring only once in the past twenty-two years (spring 1982).
5. From Cape Charles Yorke, Baffin Island, to Devon Island. This is a severe ice condition for Lancaster Sound, having occurred in two of the past twenty-two years (1970, 1984).
6. From Navy Board Inlet to eastern Devon Island across the eastern entrance to Lancaster Sound. This represents the most severe ice condition for Lancaster Sound having occurred in three of the past twenty-two years (1978, 1979, 1983).

The extent of consolidation in the western Parry Channel is much less variable than to the east. However, a small degree of variation in consolidation was noted in this study in two areas; in western M'Clure Strait and in Amundsen Gulf south of Prince of Wales Strait. A consolidated ice edge will form late each winter in

western M'Clure Strait and may occur as far west as Cape Prince Alfred, Banks Island, to Cape Kellet, Prince Patrick Island at the entrance to the Beaufort Sea (edge I, Figure 4.1). In other years, mobility in western M'Clure Strait may persist well into winter resulting in an ice edge as far east as central M'Clure Strait between Eglington Island to Cape M'Clure, Banks Island (edge G Figure 4.1). Amundsen Gulf consolidates in most years with an ice edge forming either from the southwestern tip of Banks Island or further west into the Beaufort Sea as part of the Beaufort Sea fast ice edge (edge K, Figure 4.1). In two winters of this study (1977/1978 and 1980/1981), Amundsen Gulf did not consolidate.

4.1.2 Spring and Early Summer Break-up Sequence

In the analysis of historical data on the ice cover of the Parry Channel between 1974 and 1986, fourteen discrete events have been identified as describing the pattern of break-up for the region (Figure 4.2). The average date of occurrence of these events and the range are listed in Table 4.3. The events listed in this section are sequentially listed based on the average date of occurrence for each event. Therefore, the pattern described in this section can be said to be what can be expected in an "average year". Clearly, from the analysis of Table 4.3, some events have ranges of occurrence that indicate slight overlaps with other events in some years and this should be taken into consideration in reading this section. However, although the timing of each event is an important factor in describing the break-up sequence, the pattern of events is the most important factor in aiding in the delineation of distinctive ice regimes of the Parry Channel. The following is a description of each of the fourteen break-up events of the Parry Channel found in the historical review of this thesis:

Event 1: Development of Open Water Polynyas off Consolidated Ice Edges

From the analysis of NOAA satellite imagery undertaken for this study, it

Figure 4.2: Break-up sequence for the Parry Channel. See Table 4.3 for map legend.

Table 4.3

**Break-up Sequence for the Parry Channel
1974 - 1986**

Event	Average Date of Occurrence	Range of Occurrence
1. Development of Open Water Polynyas off Consolidated Ice Edges.	Early May	Late April - Early June
2. a) Fracture of Northern Prince Regent Inlet.	June 29	June 17 - July 20
2. b) c) Fracture of Lancaster Sound.	July 17	July 1 - August 3
3. Fracture of Amundsen Gulf.	Late June	Early June - Early July
4. Fracture of eastern Barrow Strait.	July 5	June 20- July 27
5. Fracture of western M'Clure Strait.	July 8	June 24 - July 22
6. Fracture of Prince of Wales Strait.	July 15	July 6 - July 28
7. Fracture of central Barrow Strait.	July 19	July 3 - August 9
8. Fracture of Admiralty Inlet.	July 22	July 15 - August 4
9. a) b) Fracture of western Barrow Strait.	July 25	July 11 - August 10
10. a) Fracture of Wellington Channel.	July 26	July 8 - August 23
10. b) Fracture of Peel Sound.	July 26	July 16 - August 10
10. c) Fracture of McDougall Sound.	July 26	July 16 - August 10
11. Fracture of central M'Clure Strait.	July 26	July 7 - August 17
12. a) Fracture of M'Clintock Channel.	July 29	July 16 - August 22
12. b) Fracture of eastern Viscount Melville Sound.	July 31	July 12 - August 17
13. a) b) Fracture of eastern M'Clure Strait and western Viscount Melville Sound.	August 2	July 17 - August 17
14. a) Fracture of southern Byam Martin Channel.	August 8	July 20 - August 23
14. b) Fracture of northern Byam Martin Channel.	August 27	August 4 - September 12

has been found that the ice drift throughout the winter in the Canadian high Arctic is southward in Baffin Bay, eastward in Lancaster Sound and southwestward in the Beaufort Sea off M'Clure Strait and Amundsen Gulf. Since the central waterways of the Parry Channel consolidate each winter, this leaves diverging ice masses to both the east and west of the Parry Channel. Thin first-year ice continually forms throughout winter off these consolidated ice edges. However, with the return of twenty-four hour a day solar radiation in the high Arctic by late April, the first year ice formation reduces and stops such that large thin ice areas or open water polynyas develop off ice edges both to the east and west of the Parry Channel. Figure 4.3 is a NOAA satellite image from April 29, 1985, showing the full formation of the polynyas to the east and west of the Parry Channel.

The open water development is most extensive in the east with the coincident expansion of the North Water Polynya in northern Baffin Bay with the Lady Ann Polynya off Jones Sound and the clearing of Lancaster Sound. These areas join to form a large open water area in northern Baffin Bay by early June. To the west, the widening of the Cape Bathurst Polynya, located west of the consolidated ice edge in Amundsen Gulf, rapidly expands and connects with the expanding Prince Patrick Island lead opposite M'Clure Strait to form a large open water/new ice area during the same period. Such developments have been reported previously (Smith and Rigby 1981). In years when Amundsen Gulf or eastern Barrow Strait did not consolidate, these areas cleared and formed part of these respective polynyas.

Average daily temperatures do not rise above 0°C in the high Arctic until mid-June, almost one and one half months after the start of expansion of these polynyas. It is likely that the twenty-four hour solar insolation onto the dark thin ice and open water areas retards ice growth in the early spring, contributing to the creation of these polynyas, apparently once daily average temperatures rise above -10°C .

Figure 4.3 NOAA, April 29, 1985, illustrating the existence of polynyas off eastern and western consolidated ice edges of the Parry Channel.

Event 2: Fracture of Northern Prince Regent Inlet and Lancaster Sound

Northern Prince Regent Inlet will consolidate in most years (9 of 13 years of this study). It is the last area to consolidate and the first to fracture in the region. In years of Lancaster Sound consolidation, fracturing of Lancaster Sound is initiated from Prince Regent Inlet to the south. This pattern of fracture is illustrated in the NOAA satellite images of Figures 4.4 and 4.5 from July 9 and July 15, 1983, respectively. The fracturing of Lancaster Sound occurs in two stages. The first stage is the fracture of the western most segment of the Sound north of Prince Regent Inlet (area 2(b) on Figure 4.2). The second stage is the fracture of a plug of ice at the eastern entrance to the Sound (area 2(c) on Figure 4.2). This fracture pattern is a mirror image of the consolidation pattern, (see Freeze-up event 14, Section 4.3).

It has been found, in this study, that the existence of consolidation in Lancaster Sound in spring does not lead to delayed break-up for the remainder of the year. Although consolidated conditions occurred in Lancaster Sound in the springs of 1978 and 1979 which were years of delayed break-up and limited clearing, consolidated conditions also existed in the springs of 1982, 1983 and 1984 which were years of average or earlier than average break-up and clearing for the Parry Channel. The primary affect of consolidated conditions in Lancaster Sound on shipping is restricted from May to early July when extensive and at times formidable icebreaking will be required to reach points in Lancaster Sound and further west. Once Lancaster Sound has fractured by mid-July icebreaking vessels should experience little difficulty for the remainder of the summer.

Event 3: Fracture of Amundsen Gulf

The first fracturing event in the western portion of the study area is the fracture of Amundsen Gulf. This usually occurs in late June or early July. The pattern of fracture proceeds from west to east and is usually complete in one to three days.

Figure 4.4 NOAA, July 9, 1983. Note the initiation of fracture of western Lancaster Sound from Prince Regent Inlet to the south.

Figure 4.5 NOAA, July 15, 1983. The fracture noted in Figure 4.4 has expanded into western Lancaster Sound, illustrating the typical fracture sequence of Lancaster Sound.

The fractured ice melts rapidly in situ such that mostly open water conditions exist in Amundsen Gulf by late July.

Event 4: Fracture of Eastern Barrow Strait

The fracturing and/or clearing of western Lancaster Sound will leave a consolidated ice edge between Prince Leopold Island and Devon Island (edge C, Figure 4.1) each spring. The only exceptions to this pattern were the years 1974, 1976 and 1986 when the consolidated ice edge was at its minimum location in central Barrow Strait. Eastern Barrow Strait, between Prince Leopold Island and Griffith Island, will fracture rapidly over a one or two day period and this occurred on the average date of July 5 during this study. Figure 4.6 is a NOAA satellite image from June 26, 1975, which illustrates the typical pattern of this fracture. The range of timing of fracture of eastern Barrow Strait was from June 20 (1985) to July 27 (1978) during this study.

The ice of eastern Barrow Strait undergoes a rapid reduction after fracture leaving a broad, open water lead across the ice edge of Wellington Channel, Cornwallis Island and the ice edge at Griffith Island in central Barrow Strait, as can be observed in Figure 4.6. The fractured ice slowly drifts eastward past Prince Leopold Island then south into Prince Regent Inlet. The ice enters the counter clockwise flowing gyre that is present in northern Prince Regent Inlet and western Lancaster Sound. Within one week this ice has usually completely melted in situ in eastern Barrow Strait and northern Prince Regent Inlet.

Event 5: Fracture of Western M'Clure Strait

The western portion of M'Clure Strait will fracture by the middle of July and this occurred on the average date of July 8 during the historical review of this study. The area of M'Clure Strait north of Banks Island between Cape Prince Alfred and Cape M'Clure remains active well into the winter and fractures early the following summer. A NOAA satellite image from July 9, 1982, illustrates this early fracture (Figure 4.7). The typical pattern of fracture is for large pieces of

Figure 4.6 NOAA, June 26, 1975, showing uniform fracture of eastern Barrow Strait (Event 4). Note the lead development across the northern section of the Strait after fracture.

Figure 4.7 NOAA, July 9, 1982, illustrating the fracture of western M'Clure Strait (Event 5). Note the large cusp fracturing and the general westward flow trend of the ice.

2

the ice edge to cusp off and slowly drift westward toward the Beaufort Sea leaving a large area of open water. However, in some years, the ice will remain in western M'Clure Strait after fracture. The range of fracture of western M'Clure Strait during the study period was June 24 (1977) to July (1986).

Event 6: Fracture of Prince of Wales Strait

Unlike many other events in the break-up of the Parry Channel region, the fracture of Prince of Wales Strait shows very little variation from the average date of July 15. The pattern of fracture of the Strait is for the central section to decay and fracture with the remainder of the Strait fracturing shortly after. It is likely that the capture of solar radiation by the cliffs bordering the Strait creates a micro-climate that initiates the melt and fracture. The fracture of Prince of Wales Strait does not originate in any way from the earlier fracture of Amundsen Gulf to the south.

Event 7: Fracture of Central Barrow Strait

After the completion of fracture of eastern Barrow Strait, an ice edge will persist on average for one to two weeks between Resolute Bay, Griffith Island and across Barrow Strait to Somerset Island as illustrated in the NOAA image of Figure 4.6 presented previously. This ice edge usually remains intact after the fracture of eastern Barrow Strait for an average of 11 days, although this can vary between not forming at all as in the spring of 1978 to persisting for 24 days as in 1985.

The fracture of central Barrow Strait occurs rapidly between Griffith Island westward to a line joining Russell, Young, Lowther and Cornwallis Islands, and this has occurred on the average date of July 19 with a range of July 3 (1975) to August 9 (1979) during this study. This fracture is initiated by the development of open water around the small islands of central Barrow Strait during the first two weeks of July. Large expanses of open water, measuring several kilometers across, may develop north of Garrett and Lowther Islands prior to the onset of

fracture. This fracture combined with shore melting near the south and north shores of Barrow Strait, further weakens the strength of the ice cover.

Event 8: Fracture of Admiralty Inlet

The fracture of Admiralty Inlet occurs from the north to the south and has occurred on the average date of July 22 during this study. The spring ice conditions of this Inlet have been well described by others (Madison 1981, Lapp, Wells 1983, Lapp 1983, Stranberg, Embacher 1984) due to its influence on shipping to the Nanisivik mine.

Event 9: Fracture of Western Barrow Strait

The fracture of western Barrow Strait between Lowther Island and a line between the southwestern tip of Bathurst Island and the northwestern tip of Prince of Wales Island usually occurs within three days after the fracture of central Barrow Strait. A NOAA satellite image from July 23, 1977 (Figure 4.8) illustrates the completion of this event. The average date of fracture of western Barrow Strait was July 25 with a range from July 11 (1975) to August 10 (1979) during the study period.

The fracture of western Barrow Strait is usually very rapid once initiated and is aided by an early fracture of the north side of the channel along the south coast of Bathurst Island. In many years, this area will fracture prior to the initiation of fracture from the east, and this is illustrated in Figure 4.9 with a NOAA satellite image from July 6, 1982, and is depicted as event 9(a) on Figure 4.2 at the beginning of this section.

Event 10(a): Fracture of Wellington Channel

The fracturing of eastern Barrow Strait exposes an ice edge across southern Wellington Channel. This ice edge had persisted for an average of 15 days with a range of 9 to 20 days over the past 13 years. The fracturing of Wellington Channel occurred on the average date of July 26 with a range of July 8 (1985) to August 23 (1979).

Figure 4.8 NOAA, July 23, 1977, showing the completion of the fracture of western Barrow Strait (Event 9(b)).

Figure 4.9 NOAA, July 16, 1982, illustrating the early fracture of western Barrow Strait along the south coast of Bathurst Island (Event 9(a)).

The ice of Wellington Channel begins to move southwards across eastern Barrow Strait, on average, five days after the initiation of fracture, but this may occur as early as one day to as late as one month after fracture. The ice of Wellington Channel will flow slightly westward around the southeast coast of Cornwallis Island before flowing diagonally to the southeast across eastern Barrow Strait to the north shore of Somerset Island. This ice then continues eastward to Prince Léopold Island and then southward into the northern Prince Regent Inlet gyre. This ice undergoes a rapid in situ melt during this period and has usually completely disappeared, leaving open water in Wellington Channel and eastern Barrow Strait, 7 to 10 days after moving out of Wellington Channel.

Event 10(b): Fracture of Peel Sound

The fracture of Peel Sound usually occurs six days after the fracture of central Barrow Strait to the north. The average date of fracture of Peel Sound over the past 13 years was July 26. The fracturing of Peel Sound occurs rapidly from the north and is complete within one to three days.

Event 10(c): Fracture of McDougall Sound

The fracture of McDougall Sound is initiated both from Barrow Strait to the south and from Queen's Channel to the north. The fracture of southern McDougall Sound usually occurs within one day after the completion of fracture for western Barrow Strait. The average date of fracture over the past thirteen years was July 26.

The fracture of northern McDougall Sound is initiated from Queen's Channel to the north. This fracturing extends along the western shore of Little Cornwallis Island to just south of the Polaris mine site on the southern tip of the Island. The fracture of the remainder of northern McDougall Sound is delayed until the first week of August, with a small shorefast ice zone between Little Cornwallis Island and Cornwallis Island surviving until mid-August in most years. In two years of this study (1979, 1986) this area of ice survived the melt season.

Event 11: Fracture of Central M'Clure Strait

The fracture of central M'Clure Strait between Cape M'Clure, Banks Island, and Cape Vesey Hamilton, Banks Island, is initiated from western M'Clure Strait. The average date of occurrence of this event over the past thirteen years was July 26 with a range of July 7 (1981) to August 17 (1974, 1979). This fracture usually occurs, on average, three weeks after the fracture of western M'Clure Strait but may occur simultaneously on occasion. The fracture pattern is for large crescent-shaped fractures to develop from west to east as evident on a NOAA satellite image from July 28, 1976 (Figure 4.10).

Event 12: Fracture of Eastern Viscount Melville Sound, M'Clintock, Austin and Byam Channels

- Eastern Viscount Melville Sound will fracture from western Barrow Strait to the east. This occurred on the average date of July 31 during the thirteen years of this study with a range from July 12 (1975) to August 17 (1974). Fracturing occurs as a continuous progression of crescent-shaped fractures spreading westward from Barrow Strait into western Viscount Melville Sound. This fracturing also includes Austin and Byam Channels as the ice cover separates from the consolidated ice of southern Byam Martin Channel. This fracture pattern is illustrated on a NOAA satellite image from July 25, 1984 (Figure 4.11).

The fracture of northern M'Clintock Channel is initiated from Victoria Strait to the south and will often occur slightly before the fracture of Viscount Melville Sound. However, the fracture of the boundary between M'Clintock Channel and Viscount Melville Sound comes from Barrow Strait to the east and not northward from M'Clintock Channel.

The fracture of central Viscount Melville Sound proceeds to a line between Stefansson Island and the western tip of the Dundas Peninsula, Melville Island, as illustrated by the NOAA image of Figure 4.11.

Figure 4.10 NOAA, July 28, 1976, illustrating the fracture of central M'Clure Strait (Event 11).

Figure 4.11 NOAA, July 15, 1984, showing the crescent shaped fracture pattern radiating from Barrow Strait into Viscount Melville Sound (Event 12). Note the presence of a large lead from Stefansson Island to Melville Island separating the mobile ice of central Viscount Melville Sound from the consolidated ice to the west.

Event 13: Fracture of Eastern M'Clure Strait and Western Viscount Melville Sound

The final event in the break-up of the main segment of the Parry Channel is the fracture of eastern M'Clure Strait and western Viscount Melville Sound. This began on the average date of August 2 with a range of July 17 (1982) to August 17 (1974, 1979). This area will fracture from both central Viscount Melville Sound to the east as well as from central M'Clure Strait to the west.

Event 14: Fracture of Byam Martin Channel

The fracture of southern Byam Martin Channel occurs on average by August 8, six days after the fracture of Austin and Byam Channels. This fracture exposes an ice bridge between Ile Vanier and Melville Island. This ice bridge fractured in seven of the thirteen years of this study. This fracturing occurred on the average date of August 27 with a range of August 4 (1985) to September 12 (1980). This is a significant event in the break-up of the Parry Channel region as high concentrations of old ice are released into the Channel to the south from this area (see Section 4.4).

4.2 Summer and Early Fall Ice Reduction and Movement

The break-up of the Parry Channel region is usually complete by the beginning of August. The typical ice condition for the Channel after fracture is for mostly open water in Barrow Strait and Lancaster Sound east of Resolute and a high concentration of 9 to 9+ tenths condition to the west, as illustrated in a NOAA satellite image from August 25, 1974 (Figure 4.12). As with the break-up pattern described in the previous section, there are clear regional patterns to the variations in movement and clearing of sea ice for the Parry Channel. These patterns give further clues to the ice regimes of the Parry Channel and these patterns will be

described here in this section.

Ice reduction in the central and western Parry Channel is largely by in situ melt with minor amounts of ice subject to a slow eastward drift and export during the summer and early fall. A narrow stream of ice will begin to drift eastward from the high concentrations west of Griffith Island across the northern entrance to Peel Sound and will continue along the north coast of Somerset Island. Rapid in situ melt occurs with this ice such that little ice survive to reach Prince Leopold Island and exit Barrow Strait into the Prince Regent gyre of western Lancaster Sound. This ice drift is illustrated in the NOAA satellite image of Figure 4.12. Only small amounts of this ice in most years survives long enough to enter central Lancaster Sound during the summer ablation period.

Ice reduction is slow during the month of August in western Barrow Strait. A narrow lead will develop along the south coast of Bathurst Island by mid-August but this can be highly variable between July 28 (1981, 1984) to September 1 (1978). The combination of predominant northwest winds with the in situ ice reduction likely contribute to the opening of this lead. Lead development tends to be much more rapid and wider across northern Viscount Melville Sound to the west than Barrow Strait during this period. The wide lead of Viscount Melville Sound in relation to the congestion of Barrow Strait is illustrated in Figure 4.13, a NOAA satellite image from August 23, 1980.

Several authors have identified a southward slackening of ice into M'Clintock Channel as a major contributing factor in the formation of open water along southern Byam Martin and Melville Islands (Marko 1977, 1978, Markham 1981). However, in most years of this study, these open water areas developed before loosening occurred in M'Clintock Channel. In addition, formation of the large open water area along southern Melville Island is clearly unrelated to M'Clintock Channel as evident in Figure 4.10. The slow rate of southward drift into M'Clintock Channel is a likely contributing factor to the maintenance of high concentrations

Figure 4.12 NOAA, August 25, 1974, illustrating typical ice conditions after the completion of fracture for the Parry Channel. -Note high concentration of ice west of central Barrow Strait.

Figure 4.13 NOAA, August 23, 1980. Note the wide extent of the open water lead across northern Viscount Melville Sound compared to the congestion in Barrow Strait.

of ice in eastern Viscount Melville sound during the summer period and this has also been identified by Markham (1981). The ice of western Barrow Strait tends to clear much more slowly during the month of August than the ice in central Viscount Melville Sound. This delayed ice reduction may be due to the prevention of south and eastward drift of ice by Prince of Wales Island and the Islands of central Barrow Strait.

Figure 4.14 illustrates the general pattern of ice movement in the Parry Channel identified during this study for the summer and early fall. Flow patterns were more regular and consistent in Barrow Strait and Lancaster Sound than in Viscount Melville Sound or M'Clure Strait. Ice motion rates measured from NOAA satellite imagery and SAR data frequently average one nautical mile or less a day in the western Parry Channel but ten or more in the east. These findings are in agreement with others (Marko 1977, 1979, Verrall *et al.* 1974). Clearly, the stronger currents in the eastern Parry Channel (see Section 3.2.2) greatly affects ice movement whereas prevailing wind patterns influence the ice movement in the western Parry Channel.

There is a general west to east flow of the ice in the Parry Channel. The movement of southward flowing ice into the Parry Channel from northern Baffin Bay, Wellington Channel, McDougall Sound and Byam Martin Channel deflect to the west upon entering the Parry Channel. This is clearly attributable to Coriolis Force of southward moving objects in the northern hemisphere as identified by Markham (1981).

The movement of the ice in the Parry Channel creates areas of convergence where evidence of ice pressure was found on satellite images and ice reconnaissance charts. Also, areas of divergence of ice flow were identified where little to no ice pressures were likely occurring. These areas are identified in Figure 4.15. Pressure is evident on satellite images by the general brighter appearance of the ice in a congested area and the complete lack of leads.

Figure 4.14: Generalized flow of ice identified for the Parry Channel in this study.

Figure 4.15: Areas of seasonal ice convergence and divergence for the Parry Channel

The extent of ice reduction and clearing which occurs in the Parry Channel varied widely from little to no ice reduction in the western Parry Channel to almost complete clearing during the thirteen years of this study. Five patterns have been identified in this study which typify this variation.

1. Extensive Clearing of all Channels.

Overall, this was the most common variation in the degree of ice reduction identified. Extensive clearing has occurred in years where the timing of break-up occurred on or earlier than average dates. The typical pattern was for Lancaster Sound and eastern Barrow Strait to completely clear of ice by late July. This is followed by an early formation and widening of the lead in Barrow Strait and Viscount Melville Sound south of Bathurst and Melville Islands in early August. Simultaneously, large areas of open water and loosening occur in M'Clure Strait. Throughout the remainder of August the ice of western Barrow Strait, Viscount Melville Sound and M'Clure Strait undergo a rapid in situ melt. This melt continues such that ice remains in only the southern one half to one third of Viscount Melville Sound and western M'Clure Strait. However, break-up is so extensive in these years that high concentrations of old ice move south from Byam Martin Channel into eastern Viscount Melville Sound and western Barrow Strait during the months of September and October. However, little ice remains in Barrow Strait by the end of the melt season resulting in little movement of old ice eastward into Lancaster Sound in the fall and winter.

There were five years (38 percent of years) during this study when this pattern was identified (1977, 1981, 1982, 1983, 1984) with four of the years occurring consecutively. This consecutive occurrence may indicate that extensive break-up and clearing in one year may aid the development of a similar pattern the following year. This likely results from the higher than

average first year ice concentrations and possibly warmer water column conditions the following spring. A NOAA satellite image from September 24, 1982 (Figure 4.16) illustrates an example of the minimum ice extent for the Parry Channel. This image is particularly striking in that not only did extensive clearing occur in the Parry Channel in 1982, but the Byam Martin Channel ice bridge did not fracture resulting in broad, open water conditions in Viscount Melville Sound.

2. Little to no clearing of Central or Western Parry Channel.

This is second most common variation having occurred in three years (23 percent) of the study (1978, 1979 and 1986). This variation develops in years of later than average break-up and results in very limited open water development in Barrow Strait, Viscount Melville Sound or M'Clure Strait. In these years, break-up was not complete until mid-August. This is followed by the development of a narrow open water lead across southern Bathurst Island and Melville Island. The Byam Martin Channel ice bridge does not fracture leaving open water conditions across northern Barrow Strait and Viscount Melville Sound to the Dundas Peninsula, Melville Island. A high concentration of first year and old ice remain throughout Barrow Strait resulting in the extensive movement of old ice into Lancaster Sound in fall and winter (see section 4.3). A NOAA satellite image from September 20, 1978, illustrates the extent of ice cover remaining in a typical year of limited clearing of the Parry Channel (Figure 4.17)

3. Extensive Clearing of Barrow Strait and Lancaster Sound but little of Viscount Melville Sound or M'Clure Strait.

In two years of this study (1974, 1976) there was extensive clearing of Barrow Strait and Lancaster Sound but limited ice reduction in Viscount Melville Sound or M'Clure Strait. The break-up in these years occurred later than

Figure 4.16

NOAA, September 24, 1982, illustrating the minimum ice condition at the end of melt season experienced in the Parry Channel during the study period. Other similar years were 1977, 1981, 1983 and 1984.

Figure 4.17

NOAA, September 20, 1978, illustrating the maximum ice condition at the end of the melt season experienced in the Parry Channel during the study period. Other similar years were 1979 and 1986.

average, not being complete until mid-August. The pattern of ice reduction is similar to that of Pattern # 2 except that all of Barrow Strait clears of ice, unlike the previous pattern where only limited clearing occurs. This is significant in that the amount of old ice remaining in Barrow Strait at the end of the melt season affects how much ice will move eastward into Lancaster Sound in the fall (See Section 4.3).

Figure 4.18 is a NOAA satellite image from September 14, 1976, which illustrates this pattern. Note the substantially lower concentration remaining in Barrow Strait visible in Figure 4.18 compared to the NOAA satellite image from September 20, 1978 (Figure 4.17).

4. Extensive clearing of Barrow Strait and Viscount Melville Sound but not M'Clure Strait.

In two years of this study (1975 and 1980) extensive clearing occurred in Barrow Strait and Viscount Melville Sound but compact ice conditions remained in M'Clure Strait. These years were typified by having an early and extensive break-up with a rapid reduction of the ice cover of Barrow Strait and Viscount Melville Sound similar to Pattern #1. However, M'Clure Strait remained plugged with ice. In these years, the pack ice of the Beaufort Sea remained close to the coastlines of Banks and Prince Patrick Islands across the western entrance to M'Clure Strait. This may indicate that the environmental conditions that create more open water or less open water than usual in the Beaufort Sea may also affect western M'Clure Strait. Figure 4.19 is a NOAA satellite image from September 12, 1980, showing open conditions in Viscount Melville Sound compared to the close pack conditions of M'Clure Strait.

5. Extensive clearing of M'Clure Strait and Western Viscount Melville Sound but not eastern Viscount Melville Sound or Barrow Strait.

Figure 4.18 NOAA, September 14, 1976, illustrating extensive clearing of Barrow Strait but little of Viscount Melville Sound or M'Clure Strait. Compare to Figure 4.16.

Figure 4.19 NOAA, September 12, 1980. Note the open condition in Viscount Melville Sound compared to the close pack conditions of M'Clure Strait.

The final pattern identified occurred in only one year of this study (1985). This pattern is the reverse of Pattern #4 in that extensive clearing of M'Clure Strait and western Viscount Melville Sound occurred without a corresponding clearing of eastern Viscount Melville Sound or Barrow Strait. A high concentration of ice remained in Barrow Strait and eastern Viscount Melville Sound throughout the year in 1985 despite the existence of open pack conditions in western Viscount Melville Sound visible on a NOAA satellite image from September 26, 1985, shown in Figure 4.20.

4.3 Freeze-up and Winter Ice Conditions

The minimum ice condition for the Parry Channel region is achieved by mid-September. Average daily temperatures drop below -1°C after mid-September initiating the freeze-up process. The pattern of freeze-up is much less clearly definable than the corresponding pattern for break-up. Unlike break-up, where the occurrence of fracturing is easily determined from satellite and ice reconnaissance data, evidence for the occurrence of consolidation is much less easily detected. Often, consolidation will occur in the ice of an area only to be fractured once again a short while later, likely in response to wind and tidal variations. Consequently, the pattern of freeze-up for the Parry Channel is a complex array of periods of compaction and periods of mobility throughout most of the winter.

Despite the complexity of the freeze-up process, a pattern has been identified. This pattern shows strong similarities to the break-up sequence and is often a near mirror image of it. Fifteen discrete events have been identified in the historical review that typifies the freeze-up sequence. This pattern is depicted in Figure 4.21. The timing of each event in the freeze-up process can be highly variable and is identified in Table 4.4. The reason for this variation is not clear but is likely due to variations in wind speed, temperatures, and tides during the winter.

Figure 4.20 NOAA, September 26, 1985:
Note open pack conditions in M'Clure Strait
and western Viscount Melville Sound compared
to close pack conditions to the east.

Figure 4.21: Freeze-up and consolidation sequence for the Parry Channel.
See Table 4.4 for map legend.

Table 4.4
Freeze-up and Consolidation Sequence
for the Parry Channel
1974 - 1986

Event	Average Date of Occurrence	Range of Occurrence
1. Consolidation of the narrow Channels adjoining Parry Channel.	Late October	Early October - Late November
2. Consolidation of Austin Channel.	November 7	October 8 - December 14
3. Northern Wellington Channel Ice Bridge.	November 14	October 18 - December 20
4. Compaction of Western Parry Channel.	Late November	Late October - Late December
5. Consolidation of Admiralty Inlet.	mid-November	mid-October - Late December
6. Consolidation of Peel Sound.	November 22	October 23 - January 9
7. Consolidation of Southern Wellington Channel.	December 4	November 4 - January 29
8. Western Barrow Strait Ice Bridge.	December 3	October 30 - December 27
9. Consolidation of Eastern M'Clure Strait and Viscount Melville Sound.	December 14	October 27 - January 20
10. Formation of Russell Island Ice Bridge.	December 14	October 10 - January 5
11. Formation of the Griffith Island Ice Bridge.	January 9	October 24 - February 28
12. Consolidation of Western M'Clure Strait.	January 24	November 19 - March 28
13. Formation of Prince Leopold Island Ice Bridge.	February 2	December 11 - March 5
14. Consolidation of Lancaster Sound.	February 26	November 27 - March 23
15. Consolidation of Prince Regent Inlet.	March 5	December 3 - April 15

The first stages in the freeze-up process begins with the consolidation of the narrow adjoining channels to the Parry Channel. This is followed by a general west to east progression of consolidation. However, there are numerous significant regional variations, such as ice plugs in eastern Lancaster Sound and eastern Barrow Strait, which give clues to the ice regime characteristics for the Parry Channel. From a comparison of the pattern of consolidation, depicted in this Section, with the patterns depicted in the previous two Sections, the regional ice regime characteristics unfold.

The pattern of freeze-up is described as the following events.

Event 1: Consolidation of the Narrow Channels Adjoining the Parry Channel

The development and grey and grey-white ice begins in mid to late September in the western portions of the Parry Channel in Viscount Melville Sound and M'Clure Strait and expands eastward into Barrow Strait and Lancaster Sound by the end of October. The narrow channels of Navy Board Inlet, McDougall Sound, Kellet Strait, Crozier Channel and Prince of Wales Strait consolidate by late October or early November of each year.

Navy Board Inlet consolidates by late October each year. Consolidation of McDougall Sound begins in the northern part of the Sound in mid-October opposite Little Cornwallis Island and extends to the southern section of the Sound by the end of the month. Similarly, consolidation in Kellet Strait and Crozier Channels, to the north of M'Clure Strait, begins with the consolidation of Fitzwilliam Strait to the north of Eglington Island by mid-October followed by Kellet Strait and Crozier Channels by the end of the month. Consolidation of Prince of Wales Strait begins by the first week of November in the narrower northern section north of the Princess Royal Islands and extends to the wider section to the south by mid-month.

Unlike most other events in the freeze-up process, there is little variation in

the timing of consolidation of these channels. It is likely that the narrowness of these channels, combined with weak water currents (See Section 3.2.2), contribute to this early and regular consolidation pattern.

Event 2: Consolidation of Austin and Byam Channels

The second event in the freeze-up process of the Parry Channel is the consolidation of Austin and Byam Channels. This has occurred on average by November 7 with a range from October 8 (1980) to December 14 (1984). In most years this consolidation occurs long before consolidation in Viscount Melville Sound to the south leaving an ice bridge between Melville Island, Byam Martin Island and Bathurst Island. This ice edge usually has a small south-facing peak located in central Austin Channel. This peak corresponds to the general location of shallow bathymetry associated with the Keen Bank of southern Austin Channel (See Section 3.2.1). Consequently, it is likely that variations in water currents or tides associated with the shallow bathymetry of this area contribute to the formation of the ice bridge in southern Austin Channel. Figure 4.22 is a NOAA satellite image from November 20, 1975, illustrating the appearance of this feature in southern Austin Channel.

The occurrence of consolidation in Austin and Byam Channel is significant in that this stops the southward flow of old ice from Byam Martin Channel into Viscount Melville Sound in years of the fracture of the Byam Martin Channel ice bridge in the early fall.

The formation of this ice bridge usually contributes to the development of a narrow, thin-ice lead along the north side of the Parry Channel. This lead is an intermittent feature of the pre-consolidated ice of the Parry Channel in the early winter. The start of formation of this lead is visible on the NOAA satellite image of Figure 4.22. It is likely that strong northwest winds, which are the prevailing direction during this period, contribute to lead formation, and that calm winds or winds from other directions close it off. This lead has been identified,

Figure 4.22 NOAA, November 20, 1975, showing consolidated conditions in southern Austin and Byam Channels. (Event 2). Note the formation of a narrow thin ice lead across the northern part of the Parry Channel.

Figure 4.23 NOAA, October 22, 1978, illustrating the onset of compaction of the western Parry Channel during freeze-up (Event 4). Note the difference in lead pattern to that of Figure 4.22 above.

during previous investigation of the ice cover of the Parry Channel (Smiley, Milne 1979, Dey 1981), as significant to navigation during winter as it provides an area of thin ice for vessel access to southern Melville Island. Although, clearly, the occurrence of predominantly first year ice across northern Viscount Melville Sound is of significance to navigation this thin ice lead specifically, may not be significant as it has been found in this study to be very intermittent and occurs close to shorelines where the bathymetry is poor or uncharted.

Event 3: Northern Wellington Channel Ice Bridge

The third event in the freeze-up sequence is the formation of an ice bridge across the northern section of Wellington Channel between Cornwallis Island and Devon Island. This ice bridge forms the southern limit of a small area of compact ice in northern Wellington Channel east of Baillie Hamilton Island. The average date of formation of this ice bridge is November 14 with a range of October 18 (1978) to December 20 (1983) over the thirteen years of this study. The formation of this ice bridge is important since this edge stops further southward drift of old ice from Penny Strait through Wellington Channel into eastern Barrow Strait (See Section 4.4).

Event 4: Compaction of Western Parry Channel

Ice growth is the most rapid in the western portion of the Parry Channel in Viscount Melville Sound and M'Clure Strait during the early fall. Nonetheless, a high degree of mobility is maintained in the ice cover as large leads frequently open in response to winds. However, by mid to late November, the ice growth is sufficiently advanced that the mobility of the ice cover is substantially reduced. There is a clear transition from mobility to compaction, often occurring over two or three days, as leads reduce and disappear and this event is readily detected on satellite imagery. A NOAA satellite image from October 22, 1978, (Figure 4.23) illustrates the occurrence of this compaction during an early freeze-up year. A comparison between Figure 4.23 and Figure 4.22 illustrates the transition from a

mobile to a compact ice cover. Such a transition from a mobile to a compact ice cover prior to consolidation in Viscount Melville Sound has also been found by Milne (1970) during a study of under ice acoustic recording during consolidation.

The development of compaction results in few leads after late November. However, the ice cover does not consolidate usually until mid-December. The mobility of the ice cover prior to the development of compaction and the slight movement after compaction results in extensive ridging and rubbing of the developing first year ice in Viscount Melville Sound and M'Clure Strait during the fall and early winter.

Large arching north-south leads occasionally form in the ice cover of Viscount Melville Sound just prior to and during the formation of compaction in late October and November. These leads usually have a pattern similar to the lead development during fracture and are identified as dotted lines across Viscount Melville Sound in Figure 4.21. The most prominent of these leads forms between Stefansson Island in southern Viscount Melville Sound arching northwestward across Viscount Melville Sound to the Dundas Peninsula of Melville Island.

Event 5: Consolidation of Admiralty Inlet

The consolidation of Admiralty Inlet occurs in two stages. The first stage is the consolidation of the southern and central portions south of Baillarge Bay by late October. This is followed by the consolidation of the northern part of the Inlet by mid-November. The mobile ice of Lancaster Sound presses and ridges along the Baffin and Bylot Island coastlines and across the fast ice edges of Admiralty and Navy Board Inlets in the fall and winter. This creates an extensive shear zone, measuring several meters in height, by the spring of each year. This has been found to be a formidable obstacle to early spring navigation into Admiralty Inlet (Madison 1981, Lapp, Wells 1983, Sneyd 1984).

Event 6: Consolidation of Peel Sound

The consolidation of Peel Sound begins in the southern portions and advances

to near the northern entrance, on average, by November 22, with a range from October 23 (1978) to January 9 (1977). Complete consolidation of the northern entrance to Peel Sound occurs with the formation of the Griffith Island ice bridge in central Barrow Strait (Event 11). A moderate amount of ridging usually occurs across the northern entrance of Peel Sound during consolidation. However, the ice movement across the entrance to the Sound is much less than that for Admiralty or Navy Board Inlets, and this results in little or no ridge development across the entrance to the Sound.

Event 7: Consolidation of Southern Wellington Channel

The consolidation of southern Wellington Channel occurs on average by December 4 with a range of November 4 (1978) to January 29 (1984). The large range in the timing of consolidation may well be due to the strong influence of the Atlantic tide on Wellington Channel. The ebb and flow of tidal energies concentrate in Wellington Channel more so than other channels in the region (Greisman, Lake 1978). Possible variations in tidal energies between years may cause the wide range of consolidation dates.

Two ice bridges usually form in Wellington Channel, the first bridge across the northern entrance was described previously as Event 3, with the second bridge forming much later across the southern extent of the Channel at the entrance to Barrow Strait. These bridges usually form and then subsequently fracture several times during mid-winter before permanently forming for the remainder of the winter. This formation and subsequent fracture pattern gives further evidence to the influence of the tide as these events may be responding to spring and neap tides. The completion of consolidation of Wellington Channel will leave a fast ice edge between Devon Island and Cornwallis Island at the entrance of the Channel in eastern Barrow Strait and this is evident on the NOAA image of Figure 4.22 previously.

Event 8: Western Barrow Strait Ice Bridge

An ice bridge will occasionally form between the southwestern tip of Bathurst Island, to the western tip of Russell Island, located in south-western Barrow Strait. This ice bridge separates the mobile ice of western Barrow Strait from the consolidating ice of eastern Viscount Melville Sound. This is the same location where an ice bridge may occasionally form after the completion of the break-up of western Barrow Strait in the spring. This ice bridge formed in the early winter during four years of this study: 1977, 1980, 1982, and 1986. Figure 4.24 is a NOAA satellite image from November 8, 1986, illustrating the existence of the western Barrow Strait ice bridge separating the mobile ice of Barrow Strait from the consolidating ice of Viscount Melville Sound. The average date of formation of this ice bridge is December 3 with a range of October 30 (1986) to December 27 (1977) over the thirteen years of this study.

It is speculated, in this thesis, (see Section 5.2.3) that the breaching of the Atlantic tide over the shallow bathymetry of central Barrow Strait into western Barrow Strait may be a contributing factor to the increase in ice mobility in this area and the western Barrow Strait ice bridge likely forms the western most boundary of tidal penetration. This is only speculative, and, clearly, further research into this possibility should be undertaken.

Event 9: Consolidation of Eastern M'Clure Strait and Viscount Melville Sound

The formation of a fast ice edge in Barrow Strait leads shortly thereafter to the consolidation of Viscount Melville Sound and M'Clure Strait. Generally, a small degree of mobility, in the form of shore leads or across-channel fractures, will frequently occur in this region after the onset of compaction (Event 4) in early November. This compaction eventually leads to consolidation by mid-December. The determination of when consolidation has occurred is difficult from satellite and ice reconnaissance charts. For this thesis, the best estimate of when consolidation

Figure 4.24 NOAA, November 8, 1986, illustrating the existence of the western Barrow Strait ice bridge (Event 8) separating the mobile ice of Barrow Strait from the compact ice of Viscount Melville Sound.

Figure 4.25 NOAA, November 30, 1983, illustrating the formation of the Russell Island ice bridge as the mobile ice of the Parry Channel builds up behind the small islands of central Barrow Strait.

occurred was based on when evidence of mobility such as leads or wide fractures were no longer visible on images or recorded on charts. The average of estimated dates of formation of consolidation in eastern M'Clure Strait and Viscount Melville Sound is December 14 but has varied widely between October 27 (1978) to January 20 (1974) over the thirteen years of this study.

Event 10: Formation of Russell Island Ice Bridge

A major feature of the ice cover of the Parry Channel during freeze-up is the occurrence of an ice edge at Russell Island in central Barrow Strait. The general flow direction of the ice cover of the Parry Channel is from west to east, aided by a weak current and a north-west prevailing wind. The ice of Barrow Strait during freeze-up concentrates between the numerous small islands in central Barrow Strait to form an ice bridge between Russell, Young, Lowther, and Cornwallis Islands. Figure 4.25 is a NOAA satellite image from November 30, 1983, showing the typical pattern of formation of this ice bridge.

The Russell Island ice bridge may form and subsequently collapse several times during the late fall and winter months before forming permanently for the remainder of the winter. The formation of this ice bridge results in thinner ice off its eastern edge due to the continued eastward drift of the ice in central Barrow Strait. The ice behind the Russell bridge to the west may remain mobile for several weeks after the initial formation of the ice bridge. Consequently, moderate to heavy ridging will be created as this ice piles up behind the ice bridge prior to consolidation.

The average date of formation of the Russell Island ice bridge has been December 14 with a range of October 10 (1978) to January 5 (1977). During the winter of 1985-86, the Russell Island ice bridge formed the eastern limit of consolidation for the Parry Channel.

Event 11: Formation of the Griffith Island Ice Bridge

An ice bridge will occasionally form between Cornwallis Island and Griffith

Island and arch across central Barrow Strait to Somerset Island, on average, 27 days after the formation of the Russell Island ice bridge. A NOAA satellite image from January 5, 1985, (Figure 4.26) illustrates the temporary existence of the Griffith Island ice bridge. Like all of the Parry Channel ice bridges, this bridge may form and subsequently fracture several times during the winter.

Since the Griffith Island ice bridge does not form until much later than the Russell Island bridge, thinner ice with virtually no old ice or ridging can be expected in an average year in central Barrow Strait between these two locations. This is since the eastward movement of old ice from western Barrow Strait is stopped by the Russell Island ice bridge. The only exceptions occurred in the winters of 1979-80, 1981-82, and 1982-83 when the Russell bridge did not fully form and, consequently, old ice moving east from western Barrow Strait could occur behind the Griffith Island ice bridge prior to consolidation.

Once the Griffith Island ice bridge has formed, thin ice will form to the east as the eastward flowing ice continues to drift away from the ice edge. This is visible on the NOAA image of Figure 4.26. However, heavier ice growth will, at times, continue to develop in eastern Barrow Strait regardless of what occurs in central Barrow Strait and this is also evident in Figure 4.26. This heavier ice growth will eventually lead to the formation of the Prince of Leopold Island ice bridge (Event 13).

The average date of formation of the Griffith Island ice bridge has been January 9, with a range from October 24 (1978) to February 28 (1977). The Griffith Island ice bridge did not form in the winters of 1977-78, 1977-78, 1979-80, 1983-84, and 1986-87 when consolidation occurred further to the east before the bridge had a chance to develop. In the winters of 1973-74 and 1975-76, the Griffith Island ice bridge formed the eastern limit of consolidation for the Parry Channel. As with the western Barrow Strait ice bridge, tidal forces may play an important role in the formation of the Griffith Island ice bridge.

Figure 4.26 NOAA, January 5, 1985, showing the existence of the Griffith Island ice bridge (Event 11). Note the thinner ice formation to the east of the ice bridge and the development of compaction in eastern Barrow Strait which leads to the eventual formation of the Prince Leopold Island ice bridge (Event 13).

Figure 4.27 NOAA, December 6, 1986. Note the separation of mobility of western M'Clure Strait. Also note the similar ice pattern of M'Clure Strait to Amundsen Gulf.

Event 12: Consolidation of Western M'Clure Strait

Compaction and temporary consolidation will occasionally develop throughout the winter in western M'Clure Strait. However, this area will fracture and remain mobile well into the winter. This area appears to be strongly influenced by oceanographic events in the Beaufort Sea to the west and often an increase in ice mobility in western M'Clure Strait will appear to be initiated from the Beaufort Sea. A wide flaw lead will form between Eglinton Island and Cape M'Clure, Banks Island, during December at the boundary of the immobile consolidated ice of eastern M'Clure Strait and the mobile ice to the west. The pattern of mobility in western M'Clure Strait in December to January appears to mirror similar patterns and movement in Amundsen Gulf to the south. This similar pattern indicates that tidal or current variations in the Beaufort Sea may affect the ice cover of both Amundsen Gulf and western M'Clure Strait simultaneously.

The similar pattern of ice behaviour between M'Clure Strait and Amundsen Gulf is illustrated in a NOAA satellite image from December 6, 1986, (Figure 4.27). The separation of mobile ice of western M'Clure Strait from the consolidating ice of eastern M'Clure Strait is evident on the image. The similar pattern of mobility of western M'Clure to Amundsen Gulf on the image illustrates the potential influences the Beaufort Sea has on these two water bodies.

Consolidation has occurred in western M'Clure Strait on the average date of January 24 with a range from November 19 (1982) to March 28 (1977). After consolidation is complete, an ice bridge will form across M'Clure Strait at the entrance to the Beaufort Sea. This edge will form a boundary of the Prince Patrick Island lead - Cape Bathurst polynya complex during the winter and early spring.

Event 13: Formation of Prince Leopold Island Ice Bridge

The ice bridge which usually forms each winter across the eastern entrance to Barrow Strait at Prince Leopold Island represents the median eastern limit of

consolidation for the Parry Channel. This ice bridge formed the eastern limit of consolidation in 12 of the past 22 years and five of the past 13 years of this study. This ice bridge has formed on the average date of February 2 with a range of December 11 (1979) to March 5 (1985) in the thirteen years of this study.

The development of the Prince Leopold Island ice bridge is usually preceded by heavier ice growth in eastern Barrow Strait associated with a reduction in the eastward flow rate of the ice and this is evident on the NOAA satellite image from January 5, 1985, Figure 4.26, previously presented. This reduction in ice flow is likely due to reduced wind flow or tidal fluctuations during these periods. This ice bridge may form and subsequently fracture during the winter but this will occur much less frequently than is the case with the Griffith or Russell Island ice bridges. The Prince Leopold Island ice bridge forms at the western edge of the Prince Regent gyre in western Lancaster Sound and this water current boundary may be a contributing factor for the formation of an ice bridge at this location in most winters.

Once this ice bridge has formed, a reduction in ice thickness will occur off the eastern edge as the ice of western Lancaster Sound continues to drift eastward, a feature visible on the NOAA satellite image of February 7, 1984 (Figure 4.28). Heavier ice is visible on this image in eastern Lancaster Sound and this often leads to Event 14, the consolidation of Lancaster Sound, as it did on February 28, 1984 in this example.

Event 14: Consolidation of Lancaster Sound

The consolidation of Lancaster Sound has occurred in approximately 25 percent of winters over the past 22 years and 42 percent of winters in the thirteen years of this study. It has been observed, in the historical review of this study, that consolidation will occur first in eastern Lancaster Sound then spread into western portions of the Sound.

The NOAA satellite image of February 7, 1984 (Figure 4.28) mentioned above,

shows a zone of compaction in eastern Lancaster Sound with more dynamic ice occurring in western Lancaster Sound north of Prince Regent Inlet. By March 7, 1984, a lead had formed across eastern Lancaster Sound from Cape Charles Yorke, Baffin Island, to Croker Bay, Devon Island. This lead is visible on a NOAA satellite image from March 2, 1984, (Figure 4.29). This lead signalled the start of consolidation of Lancaster Sound. This example illustrates that consolidation clearly occurs in the east and then spreads to the west. Such a pattern is also observed for the formations of the other ice edges in the eastern Parry Channel such as at Prince Leopold Island and in central Barrow Strait.

The significance of this consolidation pattern for Lancaster Sound is that thicker, and more heavily ridged first year ice will occur at consolidation in eastern Lancaster Sound than in western Lancaster Sound. In addition, old ice moving eastward from Barrow Strait may not have completely cleared the Sound by consolidation and will, therefore, be more likely to occur in eastern Lancaster Sound than western Lancaster Sound by the spring. The result of this consolidation pattern is that heavier and more difficult ice conditions for icebreaking can be expected in eastern Lancaster Sound than western Lancaster Sound by the spring in years of consolidation. This may also be a contributing factor to the earlier fracture of the western portions of Lancaster Sound in the spring (see Section 4.1, Event 2).

The consolidation of Lancaster Sound occurred in five years of this study (winter 1977/78, 1978/79, 1981/82, 1983/84, 1986/87). The consolidation occurred rapidly in less than one week in each case. The usual pattern was for mobility to abruptly stop in the eastern entrance to the Sound with consolidation occurring shortly thereafter. The increased occurrence of consolidation in Lancaster Sound has been speculated to be indicative of an increase in severity of the winters in the high Arctic (Markham 1981). However, the occurrence of consolidation over a very short period would tend to indicate that local weather and hydrographic

Figure 4.28 NOAA, February 7, 1984, showing the existence of the Prince Leopold Island ice bridge (Event 13). Note the contrast of thinner ice of western Lancaster Sound to denser ice indicating heavy compaction in eastern Lancaster Sound. This compaction often leads to the consolidation of Lancaster Sound, as it did on February 28, 1984.

Figure 4.29 NOAA, March 2, 1984. Note the formation of a lead across eastern Lancaster Sound as the Sound Consolidated (Event 14).

conditions over a one or two week period may have a greater influence on the degree of consolidation in Lancaster Sound than the result of an overall seasonal weather trend. Therefore, the increased occurrence of consolidation in Lancaster Sound over the past 13 years may not necessarily be part of a longer term climatic trend.

The average date of consolidation for Lancaster Sound was February 26 during this study period, with a range of November 27 (1979) to March 23 (1978).

Event 15: Consolidation of Northern Prince Regent Inlet

Northern Prince Regent Inlet consolidated in seven of the thirteen years and is the last event to occur in the freeze-up process of the Parry Channel. The average date of consolidation of Prince Regent Inlet was March 5 which is one week later than the consolidation of Lancaster Sound. Prince Regent Inlet remains active throughout the winter with the central and southern sections rarely consolidating, even in years of complete consolidation in the Parry Channel to the north. The tendency for central and southern Prince Regent Inlet to not consolidate over the winter may be due to the propagation of the Atlantic Ocean tide into the area. A major component of the Atlantic tidal energies flowing westward through Lancaster Sound propagates southward into Prince Regent Inlet (see Section 3.21). Therefore, it is speculated here that the shoaling of these tidal energies in central and southern Prince Regent Inlet may well prevent consolidation of this area.

4.4 Old Ice Sources and Movement

The occurrence of old ice in the Parry Channel represents the most significant hazard to shipping in the area. Three primary source regions of old ice for the Parry Channel were identified in this study: The Arctic Ocean, the Sverdrup Basin north of Bathurst and Melville Islands, and old ice formed in situ within the Channel itself. Figure 4.30 illustrates these old ice source regions.

Figure 4.30: Sources and movement of old ice for the Parry Channel.
Wide arrows represent substantial movement (> 5 tenths).

The distribution of old ice within the Parry Channel varies seasonally with the highest concentration occurring between September to January. The influx of old ice from outside the Parry Channel takes place from the beginning of August and into the late winter. This influx, combined with the usual survival of some first year ice through the summer melt season each year, (which becomes old ice as of October 1 according to MANICE classification) produces extensive old ice throughout the Parry Channel during the fall. However, once consolidation in the source areas has occurred, the amount of old ice drops significantly as the influx is halted and old ice in Barrow Strait and Lancaster Sound as well as in western M'Clure Strait slowly drift out of the Parry Channel leaving large areas free of old ice by the spring. Therefore, by the end of the spring, old ice is restricted to the southern portions of western Barrow Strait and Viscount Melville Sound and eastern and central M'Clure Strait in most years.

The variation in the age distribution of ice was considered an important parameter in this study for separating the regional ice regimes for the Parry Channel. The occurrence of higher concentrations of old ice in one area as opposed to another provides important clues to the definition of regional ice regime boundaries. In this section, the patterns of old ice sources and movement for the Parry Channel will be described.

4.4.1 Arctic Ocean Sources of Old Ice

Old ice invades the Parry Channel from the Arctic Ocean in two locations. In the eastern Parry Channel, Arctic Ocean old ice flows each fall southward through Nares Strait between Ellesmere Island and Greenland into northern Baffin Bay and across and into Lancaster Sound between September and March. In the western Parry Channel old ice will, on occasion, be wind driven into western M'Clure Strait where it will slowly drift eastward into Viscount Melville Sound.

Nares Strait Source Region

It was not the intent of this study to investigate, in detail, the ice cover of the Nares Strait region, the channel separating Ellesmere Island from Greenland. However, from the analysis of the movement of old ice across Lancaster Sound in the fall it became apparent that the pattern and timing of the movement of old ice south out of Nares Strait was an important characteristic of the ice regime of the Parry Channel. Therefore, the movement of old ice out of Nares Strait was included in the historical review for this study. The details of this investigation are beyond the intended scope of this thesis but the general findings will be described here.

An ice bridge forms each winter across the southern section of the Kane Basin in Smith Sound. This bridge fractured on the average date of July 21 and showed little variation in timing during this study. The ice will remain in Nares Strait until late August when a narrow stream slowly drifts southwards along the Ellesmere Island coastline down to Smith Bay north of Coburg Island. This ice continues to drift southward to the entrance of Lancaster Sound by late September or early October in most years. During this period, old ice will invade the north end of Nares Strait from the Lincoln Sea and the Arctic Ocean.

The ice that drifts out of Nares Strait in the late summer and fall is composed of a large proportion of old ice. Initially, the ice drifting out of Nares Strait is composed of one to three tenths old ice in predominantly small and medium floe sizes. However, by mid-October in most years, the flow of ice continues such that much higher concentrations of old ice in the order of five to seven tenths in large to giant floe sizes begins to drift south past Coburg Island, aided by the continued flow of Arctic Ocean ice.

In late September old ice, in strips and patches of one to two tenths in small floe sizes, will begin to intrude into the eastern entrance to Lancaster Sound. This intrusion follows the inflowing current found along the south coast of Devon Island. This ice will intrude as far west as Croker Bay before moving south, cross-channel,

in early to mid-October, to become incorporated into the outflowing current found on the south side of the Sound.

The most significant event, as it affects navigation, is the flow of higher concentrations of old ice from Coburg Island south into Lancaster Sound by late October. This ice is composed of larger floe sizes and occurs in much higher concentrations than the first strips of old ice which intruded earlier in the month. The combination of the thickening first year ice with high concentrations of old ice, by early November, in the highly dynamic water current area at the entrance to Lancaster Sound causes a large amount of pressure and rubbing particularly north of Bylot Island. This situation has been found to create one of the greatest barriers to year-round navigation in the Parry Channel (Gorman 1987(a)). This flow of old ice occurred in this general pattern in every year of the thirteen years of this study. However, the detailed documentation of this phenomenon has been difficult until recently due to the lack of an adequate sensor to detect this ice such as has become available recently with the STAR-SAR.

The flow of old ice across the entrance to Lancaster Sound from northern Baffin Bay changes as the winter season progresses. In late October and the first half of November, the old ice intrudes into Lancaster Sound along the north side of Devon Island. This intrusion occurs as the old ice, drifting southward from northern Baffin Bay, drifts into the strong surface water current that flows eastward out of Jones Sound and geostrophically around Philpots Island into Lancaster Sound. The inflowing current carries the old ice into Lancaster Sound to Croker Bay. From here, the cross-channel flowing currents in Lancaster Sound carry the old ice to the south side of the Sound near Admiralty Inlet and then eastward once again to exit the Sound north of Bylot Island. This pattern of old ice intrusion is evident on a NOAA satellite image from November 6, 1978 (Figure 4.31). However, by late November and December this pattern changes such that the ice flows across the entrance to Lancaster Sound but does not intrude. It appears that the first

year ice developing in the current flowing eastward out of Jones Sound as well as off the shorelines of Ellesmere and Coburg Islands eventually thickens sufficiently by mid-November as to deflect the old ice drifting southward from northern Baffin Bay away from the inflowing current to Lancaster Sound. Consequently, this old ice is no longer able to intrude into Lancaster Sound but, instead, flows past the entrance. Co-incident with this deflection of old ice, the eastward mass movement of the thickening first year ice of Lancaster Sound pushes the old ice flow from northern Baffin Bay further eastward throughout the early winter such that by mid-February, the old ice stream from Nares Strait occurs in the center of Baffin Bay leaving predominantly first year ice in Lancaster Sound. The bright white floes visible on the NOAA satellite image from January 30, 1983, shows the old ice stream from Nares Strait occurring in central Baffin Bay as a likely result of the above mentioned process (Figure 4.32).

The flow of old ice out of Nares Strait ceases with the formation of an ice bridge across the southern end of the Kane Basin at Smith Sound. The old ice which occurs south of this bridge continues to flow south across the entrance to Lancaster Sound for more than a month after the ice bridge formation. The timing of formation of this bridge substantially affects the concentration of old ice which will be encountered at the entrance to Lancaster Sound for the remainder of the winter. In five years of this study (1976, 1978, 1979, 1980 and 1984 - 40 percent of years) this bridge formed before the end of the first week of December. This resulted in little to no old ice across the entrance to Lancaster Sound by early January of the following year. In three years of this study (1974, 1975, 1985 - 25 percent of the years) this bridge formed by late January resulting in little old ice by the late winter period. In the remaining years of this study (1977, 1981, 1982, 1983 - 30 percent of years) this bridge did not form until late February or March resulting in high old ice concentrations of up to five to eight tenths in northern Baffin Bay across the entrance to Lancaster Sound throughout the winter.

Figure 4.31 NOAA, November 6, 1978, illustrating the high concentration of old ice intruding into Lancaster Sound from northern Baffin Bay and Nares Strait.

Figure 4.32 NOAA, January 30, 1983. Note the flow of old ice from Nares Strait is now pushed out in the centre of Baffin Bay by the first year ice area from Lancaster Sound and Jones Sound by mid-January. Compare to Figure 4.31.

Beaufort Sea Old Ice Source Region

The movement of ice between western M'Clure Strait and the Beaufort Sea has been found, during this study, to occur both westward and at other times eastward. It is likely that water currents are slack to non-existent in this area (See Section 3.2.2) but there is little current data gathered throughout the year to support this (Markham 1981). The general trend of movement of ice in western M'Clure Strait noted during this study is westward, particularly in winter and this is indicated by the central M'Clure Strait flaw lead and this has been noted by others (Markham 1981, Verral *et al.* 1974). However, during periods of likely strong westward and north-westward winds in summer and fall, old ice has been noted from satellite images analyzed from this study, to move eastward into western M'Clure Strait from the Arctic Ocean.

It was once speculated that the movement of old ice eastward into M'Clure Strait was the primary source of old ice for the western Parry Channel; however, more recent investigations have found this to be incorrect (Markham 1981). Markham (1981) speculates that little to no ice moves eastward from the Beaufort Sea into M'Clure Strait and the ice of M'Clure Strait and western Viscount Melville Sound represents a perpetual plug of old ice. Dey (1981), on the other hand, indicates that the movement of old ice from the Arctic Ocean into M'Clure Strait and Viscount Melville Sound is a significant source. In this study neither hypothesis was found to be likely. The movement of old ice into M'Clure Strait was an infrequent occurrence brought on by the combination of high old ice concentrations close to the entrance to M'Clure Strait and corresponding strong north-west winds. The detailed analysis of such movements was not possible in this study due to the low resolution of the NOAA satellite imagery used in the analysis to detect individual floe movement. Based on the general movements noted on the NOAA satellite imagery over the past thirteen years, a speculative estimation would be that fifteen percent or less of the old ice found in M'Clure Strait at any one time

had its origins in the Arctic Ocean.

The movement of old ice eastward into Viscount Melville Sound from central and eastern M'Clure Strait was found to be a regular and consistent pattern in the fall. (See Figure 4.14). In addition, as mentioned earlier, there is a general trend for ice to move westward from western M'Clure Strait. Such a divergence from central M'Clure Strait leaves one to wonder, therefore, why there is always so much old ice in M'Clure Strait. This study has found that this area is a likely birth place for old ice and this is addressed in Section 4.4.3 on in situ old ice development.

4.4.2 Sverdrup Basin Old Ice Source Region

A large amount of old ice invades the Parry Channel, in most years, from the sea north of Bathurst and Melville Islands. This ice moves south into the Parry Channel through three channel areas. To the east, this ice moves south in the late summer and fall through Penny Strait and further into McDougall Sound and Wellington Channel entering the Parry Channel at Barrow Strait. In the central Parry Channel, old ice will invade from the Sverdrup Basin through Byam Martin Channel into Viscount Melville Sound. To the west, a small amount of old ice will flow southward from Crozier Channel and Kellet Strait into M'Clure Strait each year. The following is a description of each source region.

McDougall Sound and Wellington Channel Old Ice Source Region

The drift of old ice southward through Penny Strait occurs shortly after the completion of fracture in the Sverdrup Basin by mid-August of most years. The typical pattern of movement is for old ice to drift along the east side of Bathurst Island past Little Cornwallis Island and into McDougall Sound in late August in concentrations from trace to one tenth. As the drift continues, an ice dam will

form in mid-September between Bathurst Island and Cornwallis Island in southern Queen's Channel. This ice dam has been described previously by Lapp (1982). This dam prevents further movement of old ice into McDougall Sound. However, the continued southward drift of old ice deflects into Wellington Channel and will subsequently drift southward along the Cornwallis Island coastline into eastern Barrow Strait. Since the general flow of ice out of Wellington Channel is directly south to Somerset Island, as described in Section 4.2 of this thesis, old ice in concentrations from a trace to as high as six tenths may be encountered across eastern Barrow Strait in the fall prior to freeze-up. This old ice occurs in higher concentrations than the old ice moving through McDougall Sound earlier in the year since the ice dam north of Little Cornwallis Island tends to concentrate the old ice. In addition, since this re-direction of old ice occurs prior to freeze-up, no old ice is expected in the consolidated ice of McDougall Sound, whereas old ice can be expected in the consolidated ice along the western side of Wellington Channel. The drift of old ice through this area spans from early August to late November.

Byam Martin Channel Old Ice Source Region

A large source of old ice in the Parry Channel is the, at times, high concentrations of vast to giant old ice floes which drift southward out of Byam Martin Channel from late August to late October of most years. The movement of old ice out of this Channel is controlled by an ice bridge which forms during break-up each year between Ile Vanier and Melville Island. The fracturing of this ice bridge is described as event 15 in the break-up description of Section 4.1. This bridge has fractured in seven of the past thirteen years.

Old ice usually enters central and eastern Viscount Melville Sound two to three days after the fracture of the Byam Martin Channel ice bridge. This ice will follow the general flow pattern, as illustrated in Figure 4.30, through both Byam and Austin Channels. This ice will first flow slightly westward upon entering

Viscount Melville Sound in response to Coriolis Forces before following a south eastward trajectory to the south side of western Barrow Strait north of Prince of Wales Island. This ice becomes incorporated into the mixed old and first year ice of Viscount Melville Sound. These large floes undergo extensive fracturing during their transit from Byam Martin Channel to the south side of Viscount Melville Sound and soon become indistinguishable from the old ice of this area as interpreted from remotely sensed imagery. Due to the south eastward trend of movement, lower concentrations of old ice typically occur in eastern Austin Channel or along the south coast of Bathurst Island during the year.

Crozier Channel and Kellet Strait Old Ice Source Region

A small amount of old ice will flow each fall south westward through Crozier Channel and Kellet Strait into central M'Clure Strait from early August to late October. These Channels fracture in late July or early August. This fracture is followed by the fracture of Fitzwilliam Strait to the north by mid-August. Old ice in small to medium floe sizes will slowly drift south from the extreme western portion of the Sverdrup Basin through Fitzwilliam Strait and through Crozier Channel and Kellet Strait. This drift rate appears to be very slow but detailed assessment of this movement was not possible in this study due to the low resolution of the NOAA images in relation to the small old ice floe size in this area. The old ice which exits these Channels becomes incorporated into the old ice of central M'Clure Strait. This flow stops with the consolidation of Fitzwilliam Strait by late October.

4.4.3 In Situ Old Ice Sources

The largest source of old ice for the Parry Channel identified during this study was the Channel itself. It has been suggested that the old ice found in the Parry Channel originated primarily from the Sverdrup Basin (NORCOR 1978, APP

1981, Marko 1982). However, if one considers that the flow of old ice through Byam Martin Channel, the primary source of old ice from the Sverdrup Basin to the Parry Channel (NORCOR 1978) occurs from early September to late October in only 54 percent of the past thirteen years of this study, this alone cannot explain the vast amount of old ice found in the Parry Channel. The primary clue to this fact is that the old ice from Byam Martin Channel flows eastward into western Barrow Strait, as found in this study and by others (Norland and Canarctic 1985, Gorman, Lewis 1984). Therefore, all old ice found west of Byam Martin Channel in Viscount Melville Sound, which is where the majority of old ice is found in the Parry Channel, could not have come from the Sverdrup Basin. In fact, from the analysis of satellite and SAR imagery for this thesis, it is most likely that much of the old ice originates in the Parry Channel itself.

The accumulation of annual freezing degree days increases and melting degree days decrease westward through the Parry Channel, as do surface water temperatures. Consequently, Lancaster Sound and eastern Barrow Strait completely clear of first year ice during the summer melt season. However, in western Barrow Strait, Viscount Melville Sound and M'Clure Strait, a small amount of first year ice will usually survive the melt season. The amount of first year ice which survives the summer melt has been found to be highly variable over the past thirteen years. In some years clearing is extensive in the Parry Channel (1975, 1977, 1982, 1983, and 1984) resulting in little or no first year ice surviving into the fall period. In other years, clearing may be delayed in some or all of the Channel (1974, 1976, 1978, 1979, 1980 and 1986) resulting in high quantities of first year ice surviving.

The areas where first year ice consistently survives are in southern Viscount Melville Sound north of M'Clintock Channel as well as west of Stefansson Island and east of Prince of Wales Strait. A significant area for in situ old ice production occurs in central M'Clure Strait between Cape M'Clure and Cape Vessy Hamilton, Banks Island. This area receives the highest freezing degree days and lowest

melting degree day accumulation of the Parry Channel region (see Section 3.3.1). In addition, the water temperatures are low and currents are generally light (See Section 3.2). Therefore, the growth of first year ice in this region will be rapid during the winter likely reaching the maximum thickness of first year ice approaching 2.3 meters (Markham 1981). The ablation of the ice will be limited the following summer such that the ice survives to become second year ice by the fall. The thickness of the ice will likely be reduced only slightly by summer melt producing melt ponds and hummocks on the surface characteristic of old ice. Due to the shifting and wind driven mobility of ice during the summer, extensive ridging will develop resulting in second year ice that has most of the physical topographical features characteristics of much older ice.

The origin of the first year ice is the wide flaw lead which develops in central M'Clure Strait each winter. This lead was described in freeze-up event number 12 of Section 4.3 and illustrated in a NOAA satellite image of Figure 4.27. This first year ice drifts eastward during the summer months to become second year ice in eastern M'Clure Strait by fall. This is significant in that this winter flaw lead is likely the major birth place of old ice for M'Clure Strait. It has been noted during this study that a typical floe will move from central M'Clure eastward to Viscount Melville Sound in two to three years (See the description of SAR data, Section 5.2.1). Therefore, much of the old ice found in M'Clure Strait is likely younger forms of old ice of two to three years in age with second year ice being a major component. As mentioned earlier, only 15 percent or less of old ice in M'Clure Strait is estimated to be composed of large, thick Arctic Ocean old ice floes. Therefore, in summary, the oldest in situ formed old ice in the Parry Channel is found in southern Viscount Melville Sound (due to the eastward flow tendency of the ice from M'Clure Strait) and the youngest old ice in central M'Clure Strait. This pattern of in situ old ice growth and movement provide valuable clues to the ice regime and sub-regimes of the Parry Channel, which will be described in the

next chapter.

Chapter 5

Ice Regimes of the Parry Channel

In this chapter, the ice regime characteristics of the Parry Channel are defined and described. A number of patterns emerged as the result of an analysis of the physical environment patterns of the Parry Channel (i.e., currents, tides, water masses, and climate) described in Chapter 3 and the ice behaviour patterns (i.e., break-up, movement, and freeze-up) described in Chapter 4. These patterns form the basis of defining the ice regimes of the Parry Channel. The term "ice regime" is used, in this analysis, to describe a defined region where the ice has definable characteristics of behaviour which separates one region from other surrounding regions. Such ice related characteristics include a uniform pattern of break-up, the uniform movement of ice through the area, the pattern of freeze-up as well as the presence or absence of old ice. Since the term "regime" implies a system or method of operation (Hawkins 1981 and see Section 2.1), then the description of an ice regime must include more than just a simple description of the sea ice alone. What must also be included is a description of environmental variables which form and drive the sea ice, such as currents, tides and wind. Only through such a multi-variate description can the true "system" or "method of operation" of the ice regime be properly understood.

The first step in this analysis was to define the ice related patterns for the

Parry Channel. This is a similar approach, for example, a soil scientist would take in defining the distribution of "soil regimes" over an area. Once these patterns are defined, then causal factors in the natural environment are isolated to explain the observed pattern. For a soil scientist, such correlations are achieved through empirical studies of rainfall, parent material distribution, and elevation. Unfortunately, such an empirical correlation could not be undertaken within the scope of this analysis. Detailed quantitative measurements of such environmental variables as tides, currents or winds which correlate to the observed ice patterns of the study were not available in the data base of the physical environment of the high Arctic Islands. The data base on the physical environment of the high Arctic Islands is primarily composed of regional studies of specific factors over a defined period and are not available in detail over the thirteen year period of this study. Therefore, the analysis which follows in this chapter is a speculative discussion on the possible influences the physical environment of the Parry Channel may have on the ice distribution patterns observed in this study.

In this thesis, two "ice regimes" of the Parry Channel have been identified: the eastern Parry Channel ice regime and the western Parry Channel ice regime. In addition, these two ice regimes each have a number of sub-regime regions. These sub-regimes are areas within each ice regime which, although having characteristics which follow the general trend of the main ice regime, have one or two unique characteristics of ice behaviour which separate them from other surrounding sub-regimes. The two ice regimes and twenty sub-regimes of the Parry Channel are identified in Figure 5.1. Eleven sub-regimes, labelled 1E to 11E inclusive, have been identified in this study for the eastern Parry Channel and nine sub-regimes, labelled 1W to 9W inclusive, have been identified for the western Parry Channel. In the following two sections, these regimes and sub-regimes will be described.

To aid in the identification of these regimes and sub-regimes, synthetic aperture radar (SAR) imagery, collected over the Parry Channel during the winters of

Figure 5.1: Ice regimes and subregimes of the Parry Channel.
See legend on following page.

Figure 5.1 Legend:
Ice Regimes and Sub-Regimes of the
Parry Channel

Eastern Parry Channel
Ice Regime

1E	Northwestern Baffin
2E	Lady Ann
3E	Eastern Lancaster
4E	Admiralty
5E	Western Lancaster-
	Northern Prince Regent
6E	Eastern Barrow
7E	Wellington
8E	Central Barrow
9E	McDougall
10E	Southern Queen's
11E	Peel

Western Parry Channel
Ice Regime

1W	Western Barrow
2W	Northern Viscount
	Melville
3W	Viscount Melville-
	Eastern M'Clure
4W	M'Cintock
5W	Southern Byam Martin
6W	Prince of Wales
7W	Central M'Clure
8W	Western M'Clure
9W	Amundsen

1985/86 and 1986/87 are included. These data represent a high resolution, high quality snap shot of mid-winter ice conditions in the Channel. Although, clearly, not all ice characteristics of an ice regime will be identifiable from one image, these data will aid in the identification of many of the characteristics of each regime and sub-regime.

5.1 Eastern Parry Channel Ice Regime

The ice regime of the eastern Parry Channel includes the waterways and adjoining channels of north-western Baffin Bay, Lancaster Sound, eastern and central Barrow Strait east of a line connecting Russell, Lowther, and Bathurst Islands. The western boundary of this area corresponds to the shallow bathymetry of central Barrow Strait (see section 3.2.1).

5.1.1 Physical Environment Characteristics of the Eastern Parry Channel

The following are the prominent characteristics of the physical environment that influence the ice regime of the eastern Parry Channel:

- 1. Topography and Bathymetry**

The high topographic relief of Devon and Baffin Islands and deep water bathymetry in the eastern portion of the regime (over 1800 metres in relief and 800 metres of depth) reduces to low relief and shallow bathymetry at the western extremity in central Barrow Strait (less than 250 metres in relief and 150 metres of depth). The high relief in the eastern portion of the regime modifies the prevailing wind and increases the capture of solar radiation in near shore areas. The deep bathymetry of the eastern portion allows the warm and highly saline deep Atlantic water mass to penetrate well into the

regime. The shallow water of central Barrow Strait limits further penetration of the Atlantic water mass into the western portion of the Parry Channel and serves to shoal the incoming Atlantic tide in central Barrow Strait. —

2. Water Masses

The influence of Baffin Bay and, in particular, the Atlantic Ocean water mass may well be the most important environmental variable influencing the ice regime of the eastern Parry Channel. Due to the limiting bathymetry of 150 metres in central Barrow Strait, the upper layer of the water column of the region originates from the Arctic Ocean and has low temperatures and salinities. However, the penetration of the warmer and higher salinity Atlantic Ocean layer from 200 to 500 metres of depth has a strong influence on the surface layer. The Atlantic Ocean water mass creates surface water temperatures and salinities much higher in the eastern portion of the Parry Channel than elsewhere in the Canadian Arctic Archipelago.

The warmer surface water temperatures found in northern Baffin Bay may well be the result of upwelling Atlantic Ocean water at the shallowing continental shelf boundary in the area of the North Water Polynya. This polynya is an important factor in the early spring clearing of ice from eastern Lancaster Sound, and brings warmer air temperatures and higher precipitation in the region compared to the central and western Parry Channel.

3. Currents

Water currents are moderate to strong throughout most of the eastern Parry Channel. The predominant flow is from west to east but many counter currents occur in the region. The boundaries of the various sub-regimes of the eastern Parry Channel correspond closely to the boundaries of these counter currents. Currents vary from 7 nautical miles per day in Barrow Strait to in excess of 30 nautical miles per day at the eastern entrance to

Lancaster Sound. The currents are a significant driving force for the ice regime of the eastern Parry Channel and high ice pressures, particularly at the eastern entrance to Lancaster Sound, can be created by currents in the late fall and early winter.

4. Tides

The highest tidal range in the Parry Channel occurs in the east and is of Atlantic Ocean origin. Tidal ranges diminish from 2 to 2.5 metres at the eastern entrance of Lancaster Sound to 1 to 1.5 metres in central Barrow Strait.

The occurrence of tidal wave energy from the Atlantic Ocean through Baffin Bay into the eastern Parry Channel may have a significant effect on the ice regime of the region, particularly during spring break-up and fall and winter freeze-up. The shoaling of the spring tide into the shallow waters of central Barrow Strait likely loosens the ice cover during freeze-up in the late fall and winter months and the occurrence of the neap tide likely contributes to an increased tendency towards compaction and consolidation. Consequently, the patterns, observed during this study, of numerous temporary consolidated ice edges and subsequent fracture during the winter period in the eastern Parry Channel are likely the result of the monthly variation in the spring and neap tides in the Channel. The pattern of ice edge and lead formation in central and western Barrow Strait further supports such a hypothesis (see Section 5.1.3).

The propagation of the Atlantic tide through Nares Strait might create a similar pattern of increased or decreased tendency toward consolidation which may increase or decrease the flow of old ice through this Strait and, ultimately, into the eastern entrance to the Parry Channel.

5. Air Masses, Temperature and Precipitation

The warm, moist maritime Arctic (mA) air mass of southern Baffin Bay strongly influences the climate of the eastern Parry Channel through most of the year providing warmer temperatures and higher precipitation than those experienced in the western segment.

5.1.2 Characteristics of the Eastern Parry Channel Ice Regime

The eastern Parry Channel ice regime has the following characteristics:

1. A seasonal and highly mobile first year ice cover, with all of the first year ice that forms within the region over the winter months not usually surviving the following summer melt season, even in years of below average ice clearing for the Parry Channel.
2. Old ice is a transitory phenomenon occurring in the fall and early winter period from three source regions.:
 - a) The Arctic Ocean, moving south from Nares Strait and Northern Baffin Bay,
 - b) Western Barrow Strait moving eastward from Viscount Melville Sound and,
 - c) Sverdrup Basin moving southward from Penny Strait through Wellington Channel.

Consolidation in Barrow Strait, Nares Strait and Wellington Channel by mid-winter stops the further flow of old ice such that little old ice is encountered in the regime by the late winter, spring and early summer. The only exception is when consolidation occurs in the eastern Parry Channel ice regime before the old ice has a chance to clear the region in mid-winter. The strong surface

water currents of the eastern Parry Channel are the primary factor which flushes the old ice out of the regime.

3. Fracturing is usually complete by the end of July. The primary source region of fracture is northward from Prince Regent Inlet, then eastward into Lancaster Sound and westward into eastern and central Barrow Strait. The final stage of fracture occurs in the adjoining channels by the end of July. It is likely that, as temperatures increase, the ice gradually weakens such that a point is reached where the ice no longer has the strength to resist the vertical stresses of tidal forces or the lateral stresses of currents. When this limit is reached, the ice will fracture. Other investigators have identified wind stresses as the important factor in initiating fracture of the eastern Parry Channel (Hotzel, Nobel 1979). However, the pattern of fracture extending from Prince Regent Inlet into western Lancaster Sound, in the spring following the consolidation of the Sound the previous winter, indicates that currents and tidal stresses may be more important to fracture than wind stress. This is likely since the fracture occurs in an area surrounded by land or consolidated ice where wind cannot cause mobilization. In fact, tides may be the single most important factor as it is documented that a significant component of the Atlantic tidal energies shoal in Prince Regent Inlet (Greisman et al. 1985). Also, one should consider that the weakest axial plane of an ice sheet is in the vertical direction (Pounder 1968) which is the direction that tides will have the greatest effect.
4. Ice reduction is rapid after fracture such that open water dominates this ice regime from late August to late September. Only in severe years when limited ice reduction occurs in the entire Parry Channel are appreciable concentrations of sea ice encountered in this regime during the late summer and early fall. The strong influence of the warmer and more saline Atlantic

water mass in the eastern Parry Channel compared to the colder, Arctic Ocean dominated water mass of the western Parry Channel likely is the main contributor to the rapid melting of ice after fracture in the eastern Parry Channel ice regime.

5. Freeze-up begins in mid-September as new and grey ice formation expands from Viscount Melville Sound into Barrow Strait and reaches the eastern entrance of Lancaster Sound by early October. The channels adjoining the eastern Parry Channel ice regime consolidate by late November. The extent of consolidation of the main channel varies widely from a minimum of no consolidation at all to a maximum of the complete consolidation of Barrow Strait and Lancaster Sound. The median eastern limit of consolidation for the Parry Channel is at the eastern entrance to Barrow Strait at Prince Leopold Island.

The pattern of consolidation over the winter usually consists of numerous periods of temporary compaction and consolidation with subsequent fractures and mobility. Such a pattern is likely in response to varying winds, and tides during the winter. Consolidation is usually not complete until late in the winter with northern Prince Regent Inlet not completely consolidating until late March or early April in many years. The characteristics of the sub-regimes form an important part of the consolidation process of the eastern Parry Channel (see Section 5.1.4).

5.1.3 Characteristics of the Ice Sub-Regimes of the Eastern Parry Channel

Based on the analysis of sea ice behaviour and movement previously described in Chapter 4, eleven distinctive sub-regimes have been identified for the eastern

Parry Channel ice regime. The purpose of this section is to identify the major ice characteristics unique to each of these sub-regimes. To aid in the delineation of these sub-regimes, a SAR imagery mosaic of data collected by the Intera STAR-2 SAR system on February 14, 1987, is included in this section as Figure 5.2. In addition, a NOAA AVHRR thermal infra-red satellite image, collected on February 13, 1987, just prior to the SAR aircraft overflight, is also included in Figure 5.2. The eleven eastern Parry Channel sub-regimes are identified in Figure 5.2 as an overlay on the SAR imagery.

It is apparent from the analysis of Figure 5.2 that the SAR imagery presents the reader with different information on the ice environment than does the AVHRR image. As discussed earlier in Chapter 2, SAR imagery is a high resolution, photographic-like product that is superior to other remote sensing data in differentiating between first year ice and old ice as well as ridging in the ice environment. The AVHRR thermal infra-red image, although inadequate for old ice detection, is superior to the SAR imagery in thin ice and open water lead detection. For example, the presence of leads and thinner ice north of Prince Regent Inlet and in central Barrow Strait are evident on the NOAA image but are not readily apparent on the SAR imagery.

This satellite and SAR imagery was collected as the consolidation of Lancaster Sound was occurring in mid-February of 1987. The characteristics of each sub-regime evident on the image of Figure 5.2 are:

1. A stream of old ice is evident on the SAR as bright toned floes in northwestern Baffin Bay as well as north of Bylot Island in sub-regime 1E (northern Baffin). This old ice originated in the Arctic Ocean and entered the region through Nares Strait to the north. Extensive rubble first year ice is evident on the SAR imagery, particularly north of Bylot Island.
2. Thin, level, first year ice with little to no ridging is evident as dark toned

ice from Cobourg Island south past Philpots Island to Cape Warrender at the eastern entrance to Lancaster Sound. This area delineates sub-regime 2E (Lady Ann).

3. A consolidated ice edge is apparent in eastern Lancaster Sound between Cape Warrender, Devon Island, and Bylot Island east of Navy Board Inlet. This ice edge separates the mobile ice of northwestern Baffin Bay (ice sub-regime 1E and 2E) from the consolidating ice of eastern Lancaster Sound (sub-regime 3E). From a comparison between the NOAA satellite image and the SAR image, of Figure 5.2, it is apparent that the consolidation of Lancaster Sound began in the eastern segment. This is evident from the presence of leads in western Lancaster Sound north of Prince Regent Inlet visible on the satellite image and the existence of a "plug" of consolidated ice to the east. This plug defines the sub-regime 3E (eastern Lancaster). This consolidated ice trapped 1 to 3 tenths of old ice with extensive first year ice ridging in eastern Lancaster Sound.
4. The shear zone along the south side of eastern Lancaster Sound is discernable on the SAR imagery from the Brodeur Peninsula, Baffin Island, to Cape Liverpool, Bylot Island. This shear zone results from the grinding of the mobile ice of Lancaster Sound against the shore fast ice of Admiralty Inlet and the coasts of Baffin and Bylot Islands. This grinding produces an extensive and large ridge along the south side of the Sound. South of the ridge, in Admiralty Inlet, is the level first year ice of sub-regime 4E (Admiralty).
5. The unconsolidated ice of western Lancaster Sound and northern Prince Regent Inlet is evident by the presence of leads visible on the NOAA satellite image. These leads delineate the 5E sub-regime (western Lancaster, northern Prince Regent). An important feature of this sub-regime is that this area is the last to consolidate and the first to fracture for the Parry Channel.

6. The smooth, level first year ice with one to three tenths old ice in central Barrow Strait, sub-regime 8E, contrasts with the heavily ridged first year ice of eastern Barrow Strait, sub-regime 6E on the satellite and SAR imagery of Figure 5.2. The blockage of the east flowing ice behind the islands of central Barrow Strait creates the thin, smooth first year ice of sub-regime 8E. As this ice continues to flow eastward into eastern Barrow Strait, it becomes heavily ridged, a characteristic which is evident on the SAR imagery.
7. The level first year ice of southern Wellington Channel (sub-regime 7Ea) is interrupted to the north by the Wellington Channel north ice bridge (ice regime 7Eb) on the imagery. The Wellington Channel north ice bridge forms prior to consolidation to the north or south between northern Cornwallis Island and Devon Island. The consequence of this earlier consolidation is that old ice, drifting south from Penny Strait, dams up behind the bridge creating the old ice field located in this area and visible on the SAR imagery of Figure 5.2.
8. The level first year ice of McDougall Sound is evident on the SAR imagery (sub-regime 9E) and this contrasts with the high old ice concentrations visible to the north of Little Cornwallis Island in southern Queen's Channel (sub-regime 10E). This old ice concentration is formed in early September as old ice flowing south through Penny Strait from the Sverdrup Basin dams up between Crozier, Milne, and Bathurst Islands. This dam stops further southward movement of old ice into McDougall Sound, resulting in level first year ice free of old ice in the late fall and winter.
9. The sub-regime of Peel Sound, (11E) is located south of the arching ice edge at the northern entrance to the Sound in southern Barrow Strait and is not included on the SAR imagery.

5.1.4 Summary Characteristics of the Ice Sub-Regimes of the Eastern Parry Channel

In this section, the ice characteristics of each of the eastern Parry Channel sub-regimes will be identified. Frequent references to Figure 5.2 as well as figures and related sections from Chapter 4 and 3 will be made in this analysis.

Sub-Regime 1E - Northwestern Baffin

a) Location

This sub-regime is located in northwestern Baffin Bay and forms a bell shaped feature north of Bylot Island as depicted in Figure 5.1.

b) Prominent Physical Characteristics

The weak south flowing Canadian Current from Nares Strait and the outflowing current from Lancaster Sound are the major environmental features of this sub-regime. The mixing of these two currents north of Bylot Island create numerous counter currents and eddies in the regime.

c) Distinguishing Ice Characteristics

The movement of old ice into this sub-regime between September to March is the primary ice characteristic of this sub-regime. This old ice originates in the Arctic Ocean to the north and is carried southward by the Canadian Current through Nares Strait. A secondary source of old ice for this sub-regime is old ice flowing eastward from the western Parry Channel through Lancaster Sound. The convergence of the Canadian and Lancaster Sound surface water currents with the old ice and developing first year ice in the late fall creates high ice pressures, particularly north of Bylot Island. Old ice concentrations will typically exceed seven tenths in small to vast floe sizes by early December in this area. A description of this influx of old ice into this sub-regime is contained in Section 4.4.1 of this thesis. The lighter tones on the NOAA satellite images of Figures 4.30 and 4.31,

presented in Chapter 4, illustrate the changing distribution of the old ice field. Figure 4.31 is an image from late January of 1983 and illustrates conditions similar to those visible on the SAR and NOAA image of Figure 5.2. This occurrence of old ice in this sub-regime in the fall creates an extremely difficult ice environment for navigation in the Parry Channel (Sneyd 1983, Gorman 1985, 1987(b)).

A shear zone often develops in the fall from the north shore of Bylot Island that extends eastward into Baffin Bay. This shear zone corresponds to the southern edge of the outflowing surface water current from Lancaster Sound as it detaches from Bylot Island into Baffin Bay. To the south of this shear zone, the surface water currents are gyral and mixed. This shear zone delineates the southern extent of sub-regime 1E.

Sub-Regime 2E - Lady Ann

a) Location

Sub-regime 2E extends from Lady Ann Strait, located between Coburg and Devon Islands, south-westward to Cape Warrender, Devon Island.

b) Prominent Physical Characteristics

The prominent physical characteristic of this sub-regime is the surface water current flowing southeastward out of Jones Sound through Lady Ann Strait. It is the boundary of this current which defines this sub-regime. This current follows the coastlines of Devon and Philpots Island reaching flow rates of 30 nautical miles per day. This current enters the north side of Lancaster Sound where the velocity increases to 50 nautical miles per day. This current flows cross-channel from the north to the south side of Lancaster Sound near Cape Warrender, Devon Island.

c) Distinguishing Ice Characteristics

The existence of thin, level first year ice or open water in this sub-regime during most of the year is the primary distinguishing ice characteristic of this area. During the period from late September to mid-November, the incursion of

high concentrations of old ice into this regime from northern Baffin Bay is an additional important characteristic of this regime.

In early spring, the Lady Ann Polynya, located in Lady Ann Strait, expands southeastward with the current to create open water in this sub-regime by early May. A consolidated ice edge in Jones Sound combines with a diverging current away from this ice edge to create the Lady Ann Polynya. This open water persists in the area until the early fall.

Old ice enters this sub-regime from northern Baffin Bay and Nares Strait in late September. The wind and current assisted southward drift of old ice from Nares Strait flows past Coburg Island and subsequently into the outflowing current from Jones Sound. This occurrence of old ice into this current is significant to the ice regime of the Parry Channel as it is this current which causes the major incursion of the old ice into eastern Lancaster Sound. This strong current concentrates and moves the old ice westward into Lancaster Sound past Croker Bay. The cross channel flow disperses this old ice throughout eastern Lancaster Sound. Due to strong water currents, combined with developing first year ice and old ice, high pressures and ice rubbing are created.

The development of first year ice in this sub-regime is sufficiently advanced by mid-November as to block further movement of the old ice from northern Baffin Bay into this sub-regime. The consequence of this deflection is that no further intrusion of old ice into Lancaster Sound occurs as the old ice stream is deflected into sub-regime 1E. An example of this phenomenon was described previously in Section 4.4.1 and illustrated in Figures 4.30 and 4.31.

Level, first year ice dominates this sub-regime from mid-November until the early spring when the Lady Ann Polynya forms. This level first year ice is visible on the SAR and NOAA images of Figures 5.2.

Sub-Regime 3E - Eastern Lancaster

a) Location

This sub-regime occupies the width of Lancaster Sound from the western end of Bylot Island to the central part of the Brodeur Peninsula as depicted in Figure 5.1.

b) Prominent Physical Characteristics

The prominent physical characteristic of this sub-regime is the confused nature of the surface water currents. The south side of this area is dominated by an east flowing current which interacts with the cross-channel counter current from the north side of the Sound. This interaction creates numerous counter currents and an area where ice movement in one direction or another is often not identifiable (Marko 1982).

c) Distinguishing Ice Characteristics

The distinguishing ice characteristics of this sub-regime is the tendency for eastward flowing sea ice from western Lancaster Sound to "plug" in this area, particularly in the early to mid-winter. This is likely in response to the confused and irregular current pattern in this area which may retard the further eastward flow of ice. Examples of this phenomenon include Figure 4.2 and the consolidated plug in eastern Lancaster Sound visible on Figure 5.2. This plugging creates an ice regime with extreme ridging. In addition, since this ice has moved eastward from western Lancaster Sound, the thickest and most heavily ridged first year ice to be found in Lancaster Sound is in the eastern segment of this ice sub-regime. This plugging of ice often initiates the consolidation of Lancaster Sound.

During the spring of a year when Lancaster Sound had consolidated the previous winter, this sub-regime is the last area of Lancaster Sound to fracture. An example of this delayed fracture was illustrated in Figure 4.5.

Sub-Regime 4E - Admiralty

a) Location

This sub-regime occupies Admiralty Inlet.

b) Prominent Physical Characteristics

The 18 nautical mile width of this Inlet at the northern entrance is sufficient to allow the existence of counter currents. The current along the south side of Lancaster Sound, flowing eastward along the north shore of the Brodeur Peninsula, follows the shoreline southward past Cape Crauford into the northern entrance of Admiralty Inlet. This current flows eastward cross-channel to Cape Charles Yorke, Brodeur Peninsula, and continues eastward into Lancaster Sound. A small part of this current penetrates southward into Admiralty Inlet before turning northward along the east side of the Inlet.

c) Distinguishing Ice Characteristics

Level first year ice with a trace or less of old ice is the distinguishing ice characteristic for this sub-regime during the winter and spring. The Inlet fractures in mid- to late July with open water developing by early August. Open water predominates in this sub-regime from mid-August to late September.

Ice formation begins in late September with consolidation occurring in the southern two thirds of the Inlet by mid-October and the northern section by early to late November. The interaction of the current and wind driven ice cover of Lancaster Sound with the consolidating level first year ice of Admiralty Inlet creates a complex pattern of large shear zone ridges and areas of rubbled first year ice and old ice in the fall and winter. The flow of water currents into Admiralty Inlet across the northern entrance creates a north facing, crescent-shaped arch to the consolidating ice edge of Admiralty Inlet in most years. Near Cape Crauford, an area of rubbled first year ice and old ice is created as is a similar area on the east side. These features, combined with the complex shear zone ridge across the entrance to the Inlet, are visible on the SAR imagery of Figure 5.2.

Sub-Regime 5E~ Western Lancaster - Northern Prince Regent

a) Location

This sub-regime occupies the entire width of western Lancaster Sound from central Brodeur Peninsula to Prince Leopold Island as well as the northern part of Prince Regent Inlet as depicted on Figure 5.1.

b) Prominent Physical Characteristics

The prominent physical characteristic of this sub-regime is the counter clockwise surface water current gyre found in western Lancaster and northern Prince Regent Inlet. The movement of Atlantic tidal energies into northern Prince Regent Inlet from Lancaster Sound is also an important characteristic.

c) Distinguishing Ice Characteristics

Unlike eastern Lancaster Sound (sub-regime 3E) which is a zone of ice compaction, this sub-regime is characterized as having generally high sea ice mobility throughout the year. This mobility is likely in response to the dynamic water currents in this area and the possible shoaling of the Atlantic tide as it propagates southward into Prince Regent Inlet.

The fracture of the eastern Parry Channel is initiated from this sub-regime in years when the consolidated ice edge is located in eastern Lancaster Sound. Fracturing begins in northern Prince Regent Inlet then expands northward into western Lancaster Sound within one week. The subsequent fracture of eastern Barrow Strait and eastern Lancaster Sound occurs shortly thereafter. Figures 4.4 and 4.5 illustrate this break-up sequence.

In years when the consolidated spring ice edge is located in Barrow Strait, this area clears of ice in mid-May to become part of the Lady Ann and north water polynyas.

In late July and August, this ice regime serves as the major ablation area for first year and old ice moving eastward from Barrow Strait. This east flowing ice enters northern Prince Regent Inlet and circulates in the gyre as it ablates.

In the late fall and winter, a boundary between a lead-dominated ice condition of this sub-regime and the compact ice of eastern Barrow Strait (sub-regime 6E) often occurs. This boundary results from the separation of compact conditions in eastern Barrow Strait, where the eastward moving and thickening ice dams up causing extensive first year ice ridging and few leads, contrasting to the thinner, and more mobile ice of western Lancaster Sound. This boundary forms the median limit of consolidation for the Parry Channel. The occurrence of compaction to the east of sub-regime 5E in eastern Lancaster Sound (sub-regime 3E) during the same period, makes this sub-regime a region of thinner, more mobile ice than to the east or west during the winter. Consequently, in years when consolidation includes all of Lancaster Sound, this sub-regime is the last region to consolidate for the Parry Channel. The above mentioned phenomenon of more mobile and thinner ice in western Lancaster Sound than to the east or west is visible on satellite images presented in the previous chapter as Figure 4.26, and Figure 4.28,. The NOAA satellite image of Figure 5.2 also illustrates this phenomena.

Sub-Regime 6E - Eastern Barrow

a) Location

This sub-regime occupies eastern Barrow Strait, from Prince Leopold Island to the east to a line joining Cornwallis, Griffith, and Somerset Islands to the west.

b) Prominent Physical Characteristics

The prominent physical characteristic of this sub-regime is the moderate, 7 nautical miles per day, east flowing current which occurs along the south side of the regime north of Somerset Island. This current meets with the stronger south-east flowing current from Wellington Channel in the eastern most section of the regime.

c) Distinguishing Ice Characteristics

This sub-regime is characterized by a uniform pattern of fracture during the

spring break-up period and a uniform pattern of consolidation in the mid-winter. Complete fracture occurs over a short time. An example of the complete fracture was illustrated previously on Figure 4.6. The ice melts rapidly after fracture as it slowly drifts eastward into the gyre present in western Lancaster Sound (sub-regime 5E).

This sub-regime receives first year and old ice from western Barrow Strait and Wellington Channel throughout the summer and fall. Due to the southward flowing current from Wellington Channel and the concentration of the east flowing current from central Barrow Strait on the south side of the regime, the drifting old ice concentrates along the south side leaving open water conditions along the north side throughout the summer and early fall.

The most significant characteristic of this ice regime occurs in the late fall and early winter. This sub-regime is characterized as having thick, compact, first year ice and old ice compared to the thinner ice and lead-dominated ice of central Barrow Strait to the west (sub-regime 8E) and western Lancaster Sound to the east (sub-regime 5E). As the thin first year ice moves eastward from central Barrow Strait, in fall and winter, it becomes thicker and more heavily ridged as it moves through eastern Barrow Strait. However, a clear boundary to a more dispersed ice occurs in western Lancaster Sound east of Prince Leopold Island. This contrast between the thin ice of central Barrow Strait and the lead-dominated ice of western Lancaster Sound with the compact ice of eastern Barrow Strait shows up clearly on NOAA satellite imagery during the winter. Examples presented in this thesis were Figure 4.26 and the NOAA satellite image of Figure 5.2. The mechanism of compact, thick first year ice creates a "plug" and often leads to consolidation of eastern Barrow Strait creating an ice edge at Prince Leopold Island. This consolidation occurs first in eastern Barrow Strait then spreads westward into central Barrow Strait. This compaction occurs so commonly during the winter period that the ice edge at Prince Leopold Island forms the median eastern limit

of consolidation for the Parry Channel, occurring in over 50 percent of winters.

Sub-Regime 7E - Wellington Channel

a) Location

This sub-regime occupies all of Wellington Channel and has two sections: a southern section between Cornwallis Island and Devon Island and a northern section occupying the small sea east of Baillie Hamilton and Devon Islands.

b) Prominent Physical Characteristics

The prominent physical characteristics of this sub-regime is the moderate 17 nautical miles per day south flowing current from the Queen's Channel. The shoaling of the Atlantic tidal energies into this sub-regime, particularly in the northern section (sub-regime 7Eb) may increase ice movement and likely is a contributing factor in the persistence of a small polynya in Pioneer Channel (located between Dundas Island and the Grinnell Peninsula, Devon Island as identified on the SAR of Figure 5.2).

c) Distinguishing Ice Characteristics

The southern section of this sub-regime fractures uniformly, usually within one day in late July, with the fractured ice flowing southward into eastern Barrow Strait (sub-regime 6E) and melting there as well as in the gyre located in western Lancaster Sound (sub-regime 5E). The northern part of this sub-regime (7Eb) fractures shortly after the southern section. Open water develops soon after fracture by early August.

An important feature of this sub-regime, as it affects ship navigation through eastern Barrow Strait, is the movement of the, at times, high concentration of old ice south through Wellington Channel from the Queen's Channel in the fall and early winter (Gorman 1987(a)). This movement is initiated in early September by the formation of a dam of old ice in the southern Queen's Channel between Little Cornwallis and Bathurst Islands. This dam stops further southward movement of

old ice from the Sverdrup Basin into McDougall Sound from Penny Strait. Old ice overflows the dam eastward through the Maury Channel into Wellington Channel in September, creating a stream of old ice along the eastern shore of Cornwallis Island. The concentration of old ice begins as a trace to one tenth early in the fall but may increase to four or more tenths by late October and November. By mid-November an ice bridge usually forms across the southern extent of sub-regime 7Eb. This ice bridge, which occurs as a result of compaction and consolidation in 7Eb, stops the further southward movement of old ice into southern Wellington Channel and the damming of old ice behind it, is evident on the SAR imagery of Figure 5.2. The consolidation of southern Wellington Channel (sub-regime 7Ea) occurs in early December, one month after the consolidation to the north. The ice bridges in this sub-regime were observed, from satellite imagery, to form and subsequently fracture several times during a typical winter. It is likely that the ebb and flow of the Atlantic tide is a contributing factor to this pattern as a significant component of the Atlantic tide has been measured to flow through Wellington Channel (Griesman, Lake 1978).

Sub-Regime 8E - Central Barrow

a) Location

This sub-regime occupies the area of central Barrow Strait east of Russell, Young, and Lowther Islands and west of a line joining Griffith Island to Somerset Island and sub-regime 6E.

b) Prominent Physical Characteristics

There are three prominent physical characteristics of this sub-regime:

1. The Islands of Russell, Young, and Lowther act as a barrier to the mass movement of east flowing ice from western Barrow Strait, particularly in the fall and winter.

2. A weak, counter clockwise surface water current gyre exists in central Barrow Strait (see Figure 3.2).
3. The shallowest threshold bathymetry for the Parry Channel of 150 metres occurs in this sub-regime. This shallow bathymetry serves to shoal the incoming Atlantic tide from eastern Barrow Strait thereby likely increasing tidal wave heights and energies in this area.

c) Distinguishing Ice Characteristics

The primary distinguishing ice characteristic of this sub-regime is the strong contrast between this regime and western Barrow Strait (sub-regime 1W and 3W). Sub-regime 8E is characterized by generally low old ice concentrations and the thinnest first year ice is likely to be found in the Parry Channel through much of the early winter in most years.

The ice of this sub-regime fractures by mid-July, aided by the earlier melt around small islands to the west. Upon the completion of fracture, the ice drifts eastward and melts soon after fracture in eastern Barrow Strait (sub-regime 6E). Open water with small amounts of old ice drifting eastward from western Barrow Strait typify the mid-summer from late July to early September for this sub-regime.

The damming of the east flowing old ice and thickening first year from western Barrow Strait around Russell, Young, and Lowther Islands in the fall is an important feature of this sub-regime. The development of grey, grey-white and thin first year ice causes the east-flowing ice mass from western Barrow Strait to congeal to form a large ice sheet. Once this ice mass takes form, usually in mid-to late October, there is a greater tendency for the ice to become trapped behind the islands of central Barrow Strait. This dam inhibits old ice and thicker forms of first year ice from reaching central Barrow Strait from the west. That which does pass into eastern Barrow Strait does so primarily through the narrow gap of 15 nautical miles which exists between Young and Lowther Islands. Conse-

quently, new ice develops east of these islands which slowly drifts eastward and thickens toward eastern Barrow Strait in the early and mid-winter. This newly formed ice contains much lower concentrations of old ice than in western Barrow Strait. Therefore, the thinnest first year ice, with the least amount of ridging, is to be found in this sub-regime during the late fall and early winter for the Parry Channel. An example of this phenomenon of ice damming behind the islands in central Barrow Strait and the resultant thinner first year ice to the east are evident on the NOAA satellite image and SAR of Figure 5.2. Note the development of thicker forms of first year ice as this ice moves eastward in Barrow Strait. This is evident by the transition from dark, warm ice (thinner) in central Barrow Strait to brighter, colder (and thicker) ice in eastern Barrow Strait. Other examples of this phenomenon, were presented earlier as Figures 4.25 and Figure 4.26.

The consolidation of the central Barrow ice regime occurs in most winters and results from either the earlier consolidation in eastern Barrow Strait or Lancaster Sound (sub-regime 6E or 3E) or from the formation of an ice bridge between Griffith Island and Somerset Island (freeze-up Event 11, of Section 4.3). This ice bridge has been observed, in this study, to form and subsequently fracture several times during the winter. This pattern may well be in response to the monthly variation in spring and neap tides in the eastern Parry Channel. It is well known that the shoaling of tidal waves in shallow water serves to increase tidal heights and energies (Forrester 1983) and this may well be the process which influences the occurrence of consolidation in central Barrow Strait. However, a detailed correlation of tidal heights with the occurrence of consolidation is required in order to prove such a hypothesis.

Sub-Regime 9E - McDougall

a) Location

This sub-regime occupies McDougall Sound and Resolute Passage from Lit-

the Cornwallis Island to a line joining Bathurst Island to Lowther, Griffith and Cornwallis Islands.

b) Prominent Physical Characteristics

The prominent physical characteristic of this sub-regime is the weak current flowing southward from the Queen's Channel to Barrow Strait. The tidal range is complex since tidal energies flow into this sub-regime from both the north through Crozier Strait and the south from Barrow Strait resulting in opposing tidal waves.

c) Distinguishing Ice Characteristics

The distinguishing ice characteristics of this sub-regime include:

1. Fracture of this ice regime is initiated in late July both from the Queen's Channel to the north as well as from Barrow Strait to the south. This corresponds to the same pattern as the tidal energies which flow into this regime.
2. The occurrence of a trace to two tenths of old ice in small floe sizes drifting southward from the Queen's Channel in August and early September.
3. The stoppage of the flow of old ice on average by early September by the formation of an ice dam in the southern Queen's Channel (sub-regime 10E) creating an old ice free environment for this sub-regime from the September to July.
4. Level first year ice throughout the late fall and winter. This level first year ice is evident on the SAR of Figure 5.2.

Sub-Regime 10E - Southern Queen's

a) Location

This sub-regime is bounded to the north by Crozier Island and to the south by a line joining Bathurst Island to the southern tip of Little Cornwallis Island.

b) Prominent Physical Characteristics

There are two important physical characteristics that influence this ice sub-regime. These are:

- 1) The occurrence of the numerous small islands in southern Queen's Channel which serve to dam the southward drifting ice from the Sverdrup Basin through Penny Strait, and

- 2) The splitting of the southward flowing current from the northern Queen's Channel southward into McDougall Sound and eastward into the Maury Channel.

c) Distinguishing Ice Characteristics

The prominent ice characteristic of this sub-regime is the dam of old ice which forms in the area north of Little Cornwallis each September. This blockage stops the further southward movement of old ice into McDougall Sound (sub-regime 9E) and redirects the flow of old ice eastward through Maury Channel into Wellington Channel (sub-regime 7E). This causes a shift in the flow of old ice from the Sverdrup Basin from central Barrow Strait to eastern Barrow Strait. This ice dam is evident on the SAR of Figure 5.2 and is identifiable as the bright return of old ice and rubbled first year ice in this area.

Sub-Regime 11E - Peel

a) Location

This sub-regime occupies the area of Peel Sound.

b) Prominent Physical Characteristics

A weak counter current occurs in this Sound. A weak south flowing current from Barrow Strait along the west side of the Sound is opposed to the east by a weak north flowing current from Franklin Strait to the south. Tidal energies originate from the south and are much weaker than that which pass across Barrow Strait to the north.

c) Distinguishing Ice Characteristics

The important ice characteristic of this sub-regime as it affects the Parry Channel is the general lack of interaction of the ice of this Channel with Barrow Strait to the north. Although old ice does, at times, drift south from Barrow Strait into Peel Sound, most of the ice flows across the entrance continuing eastward and does not intrude. It is possible that the behaviour of break-up, freeze-up and ice movement of Peel Sound is more closely related to Franklin Strait to the south than to the Parry Channel. However, an ice study of these water bodies similar to this study would be required to identify this possibility.

5.2 Western Parry Channel Ice Regime

The ice regime of the western Parry Channel includes the waterways and adjoining channels of M'Clure Strait, Viscount Melville Sound and Barrow Strait west of a line connecting Russell, Lowther, and Bathurst Islands. The eastern boundary of this regime corresponds to the shallow bathymetry of central Barrow Strait (see Section 3.2.1).

5.2.1 Physical Environment Characteristics of the Western Parry Channel

The following are the prominent physical environment characteristics that influence the ice regime of the western Parry Channel:

1. Topography and Bathymetry

The low lying topography and level 500 metre continental shelf bathymetry is characteristic of the western Parry Channel and this contrasts to the deep glaciated canyon and high mountainous relief which are characteristics of the eastern Parry Channel. The low lying relief results in little topographic modification of the prevailing winds in the region. The broad continental

shelf of the Beaufort Sea extends deep into the western portion of the Parry Channel.

2. Water Masses

The influence of the Arctic Ocean water mass is an important environmental parameter influencing the ice regime of the western Parry Channel. There appears to be little interaction between the underlying Atlantic Ocean layer with the overlying Arctic Ocean layer in the western Parry Channel unlike the eastern Parry Channel where the intrusive Atlantic Ocean water from Baffin Bay dominates the upper water column. This lack of interaction in the western region results in surface water temperatures and salinities much lower in the western Parry Channel than the eastern Parry Channel. The contrast between an Arctic Ocean water mass dominated western Parry Channel to an Atlantic Ocean water mass dominated eastern Parry Channel may well be the cause of the strikingly different characteristics of each ice regime.

3. Currents

Surface water currents are weak to non-existent throughout the western Parry Channel. The currents in the region are the result of the slow eastward flow of water from the Arctic Ocean through the Archipelago to Baffin Bay and the Atlantic Ocean. A weak flowing eastward current at 0.5 nautical miles per day in M'Clure Strait gives way to an indiscernible current in Viscount Melville Sound. The only consistent current is a moderate current of 10 nautical miles per day which flows southwards then eastward out of Byam Martin Channel into Viscount Melville Sound.

The weak currents of the western Parry Channel contrast markedly to the moderate to strong currents found east of central Barrow Strait in the eastern Parry Channel. These weak currents result in an ice regime with much slower

ice movements such that little clearing of ice by export occurs in the western Parry Channel.

4. Tides

Tides are low in the western Parry Channel, averaging 0.5 metres or less throughout most of the region. The tides are mixed mainly semi-diurnal with two high waters and two low water tides each lunar day but with marked irregularities in height and spacing. However, a small anomaly occurs along the south shore of Melville Island in northern Viscount Melville Sound where higher tidal ranges of up to 1.5 metres are experienced and the tides are semi-diurnal but are nearly equally spaced in timing and range throughout each lunar day.

The tides of most of the western Parry Channel are of Arctic Ocean origin but some tidal energies from the Atlantic Ocean breach the shallow water of central Barrow Strait and enter the western Parry Channel in western Barrow Strait. Due to the shallow bathymetry found along the south shore of Bathurst Island, this tidal energy may be shoaled and intensified in this area.

5. Air Masses, Temperatures and Precipitation

The cold, dry continental Arctic (cA) air mass centered over the Arctic Ocean strongly influences the climate of the western Parry Channel throughout most of the year providing colder temperatures and lower precipitation than found in the eastern Parry Channel. Prevailing winds from the northwest dominate the western Parry Channel throughout most of the year unlike the eastern Parry Channel where cyclonic winter storms in Baffin Bay provide more variable winds. The interaction of the strong north-west winds with the flat lying topography of the region and the lack of strong currents make wind the main driving force for the ice regime of the western Parry Channel.

5.2.2 Characteristics of the Western Parry Channel Ice Regime

The western Parry Channel ice regime has the following characteristics:

1. A mixed old ice and first year ice cover that has limited mobility, with some of the first year ice that forms over the winter months surviving the following summer melt season each year.
2. Old ice is a perennial feature of this ice regime from three source regions:
 - a) Old ice that forms In situ. Old ice that forms from first year ice within the regime is the largest single source of old ice with central M'Clure Strait being the primary source region.
 - b) Old ice moving eastwards from the Beaufort Sea and the Arctic Ocean into M'Clure Strait.
 - c) Old ice from the Sverdrup Basin which flows southward through Byam Martin Channel into Viscount Melville Sound with a minor secondary source through Crozier Channel and Fitzwilliam Strait into M'Clure Strait.

Old ice concentrations are at the highest in the western Parry Channel in October to December when the surviving first year ice has become second year ice in the region and the influx from Byam Martin Channel and the Arctic Ocean has ceased. Old ice is at its minimum in the early September when ablation is at its peak and the influx of old ice from outside the region has not yet peaked.

3. Fracturing is usually not complete until early to mid-August. The primary source regions for fracture are westward from Barrow Strait and eastward

from western M'Clure Strait. The final stage of fracture occurs in eastern M'Clure Strait and western Viscount Melville Sound.

4. Ice reduction is very slow after fracture with extensive open water developing usually only in the northern sections in most years. There is a high degree of variation in the extent of clearing with extensive clearing occurring in approximately 30 percent of years and almost no clearing occurring in another 30 percent of years.
5. Freeze-up begins in early September with the formation of new and grey ice over all waterways. Numerous open water and young ice leads develop throughout the early fall likely in response to shifts in wind speeds. A clear transition develops each year in mid to late November between a generally loose and mobile ice cover to a compact ice cover with few leads in the western Parry Channel.

Consolidation is usually complete by mid-December and there is very little variation in the extent of consolidation with all waterways completely consolidating every year except for the extreme western portion of M'Clure Strait.

5.2.3 Characteristics of the Ice Sub-Regimes of the Western Parry Channel

Based on the analysis of sea ice behaviour and movement undertaken for this study, and discussed previously in Chapter 4, nine ice sub-regimes have been identified for the western Parry Channel ice regime.

The purpose of this section is to identify the major ice characteristics unique to each of these sub-regimes. To aid the delineation of these sub-regimes, two SAR imagery mosaics of data collected by the Intera STAR-1 SAR system on December

7 and 8, 1986, (Figure 5.3), and on February 5, 1986 (Figure 5.4), are included in this section. In addition, a NOAA thermal infra-red satellite image, collected on December 6, 1986, is presented in Figure 5.3 along with the concurrently collected SAR data. A NOAA thermal infra-red image from January 24, 1986, is included with the SAR imagery of February 5, 1986 of Figures 5.4. Eight of the western Parry Channel sub-regimes are included in Figures 5.3 and 5.4 as overlays to the SAR imagery.

The SAR and satellite imagery of Figure 5.3 were collected in early December of 1986 of the eastern portion of the western Parry Channel. The 1986 ice year was characterized as having below average temperatures and a resultant limited ice break-up and clearing compared to the other years of this study. Therefore, the early winter ice conditions depicted in Figure 5.3 are typical of a winter following a year of below average clearing. This figure is a good illustration of the contrast between the low old ice concentrations and high ice mobility of the eastern Parry Channel (represented with sub-regimes 6E to 11E on Figure 5.2 previously) with the high old ice concentration and limited mobility of the western Parry Channel (represented with sub-regimes 1W to 7W on the Figure 5.3). The characteristics of the western Parry Channel ice sub-regimes 1W to 7W evident on the imagery of Figures 5.3 are:

1. The low old ice concentration of north-western Barrow Strait south of Bathurst Island of sub-regime 1W is evident on the SAR imagery. Of particular note is the large crescent-shaped ice bridge spanning from Russell Island north-westward to Bathurst Island visible on the SAR imagery and particularly striking on the NOAA satellite image. This ice bridge separated the consolidated ice of Viscount Melville Sound from the still mobile ice of Barrow Strait. This ice bridge is a common occurrence in both the spring break-up and fall freeze-up. It is speculated here that this edge forms the western most penetration of the Atlantic tide into the Parry Channel and that the

Figure 8.3 STAR-1 SAR Mosaic of Western Parry Channel Ice Regime, December 7 & 8, 1990.

Figure 5.4 STAR-1 SAR Mosaic of Western Perry Channel Ice Regime, February 5, 1996

shoaling of the tide along the shallow bathymetry south of Bathurst Island may well be what is keeping the ice cover of Barrow Strait mobile later in the winter.

2. The large area of first year ice along the northern part of Viscount Melville Sound and all of Byam and Austin Channels is visible on the SAR imagery (sub-regimes 2W and 5Wa). This area covers all of southern Byam Martin Channel and Byam and Austin Channels due to the persistence of the ice bridge in 1986, which forms each year in central Byam Martin Channel between Ile Vanier and Melville Island, ~~preventing the~~ influx of old ice from entering the Parry Channel. This bridge is identified on the SAR imagery of Figure 5.3.

The extent of first year ice across northern Viscount Melville Sound is narrow on Figure 5.3. This is due to the limited amount of ice reduction which occurred in Viscount Melville Sound in 1986.

3. The vast area of 9 tenths old ice in floe sizes ranging from small to giant across central in southern Viscount Melville Sound and all of eastern M'Clure Strait is identifiable on the SAR imagery of Figure 5.3 (sub-regime 3W and 6W). This area is extensive on this imagery due to the limited melt of 1986. The area between the western tip of Melville Island and Prince of Wales Strait, located in the lower left hand corner of the SAR, likely represents a significant old ice barrier to navigation for the Parry Channel.

The satellite and SAR imagery of Figure 5.4 were collected in late January and early February of 1986 of the western portion of the western Parry Channel ice regime. These data were collected after 1985 which was a year having above average temperatures and a resultant extensive break-up and clearing for the Parry Channel. Therefore, Figure 5.4 illustrates typical mid-winter conditions in the western Parry Channel following a summer and fall of above average temperatures

and break-up. Figure 5.4 contrasts with Figure 5.3 which is imagery of winter conditions after a below average year and a number of significant differences in ice distributions are identified between these two Figures.

The characteristics of the western Parry Channel ice sub-regimes 1W to 8W evident on the imagery of Figure 5.4 are:

1. The wider extent of first year ice across the northern part of Viscount Melville Sound (ice regime 2W) is evident on the SAR of Figure 5.4 compared to Figure 5.3. However, a major difference in the distribution of old ice in Byam Martin, Byam and Austin Channels is evident on Figure 5.4 compared to Figure 5.3. The ice bridge at Ile Vanier in Byam Martin Channel fractured, in the summer of 1985 releasing a high concentration of old ice which drifted southward through Byam Martin Channel into Viscount Melville Sound. This old ice is evident in these channels on Figure 5.4. During the summer and fall of 1986 the Ile Vanier ice bridge did not fracture and, consequently, no old ice is visible in southern Byam Martin, Byam and Austin Channels on the SAR imagery of Figure 5.3.
2. The distribution of old ice in central and southern Viscount Melville Sound (sub-regime 3W) as well as eastern M'Clure Strait (sub-regime 5W) is much more open and dispersed on Figure 5.4 than on Figure 5.3. This is due to the greater amount of ablation of the ice cover which occurred during the 1985 melt season compared to 1986.
3. The distribution of ice in M'Clure Strait, evident on the imagery of Figure 5.4, gives clues to the behaviour and dynamics of the ice sub-regimes of the Strait (sub-regime 6W, 7W and 8W). The eastern portion of M'Clure Strait (sub-regime 7W) is congested with a high concentration of old ice. Two giant old ice floes, marked as floe A and B on Figure 5.4, dominate eastern M'Clure Strait. These floes are surrounded by smaller old ice floes that appear to

show slightly less volume scattering (i.e., slightly darker appearance) than the two giant old ice floes on the SAR imagery. In addition, the two giant old floes show a much brighter return on the thermal infra-red NOAA image of Figure 5.4 indicating a colder temperature than the surrounding old ice.

Giant floe "B" had drifted across the entrance to Prince of Wales Strait, during the summer of 1986, and was encountered by the Canadian Coast Guard during a probe of the northwest passage by the vessels CCGS Sir John A MacDonald and the MV Kalvik. One level ice thickness core of this floe, taken by a field party during the voyage, measured in excess of 6 metres (Capt. D. Johns, Canadian Coast Guard, pers. com., 1987). It is speculated here and in Section 4.4.1 previously, that these giant old ice floes have their origin in the Arctic Ocean, while the smaller floes situated around these larger floes were formed in situ in M'Clure Strait. Evidence of this is the apparent difference in radiometric properties of higher volume scattering from the giant old ice floes, great thickness and colder temperatures which are indicative of very old ice compared to the surrounding smaller floes. The smaller floes are likely much younger than the giant floes having formed only two or three years earlier in central M'Clure Strait.

Evidence of the formation and age of the old ice formed in situ in M'Clure Strait can be found on the SAR imagery of sub-regime 7W of Figure 5.4. The wide, level first year ice flaw lead of central M'Clure Strait is clearly visible on the SAR satellite imagery. The processes involved in the formation of this lead have been described previously in Section 4.3, freeze-up event 12. To the east of this flaw lead is an area of old ice with medium to vast floe sizes which makes up the eastern end of sub-regime 7W. It is speculated here that the old ice found in the eastern end of sub-regime 7W is predominantly second year ice (as of October 1, 1985), having drifted eastward from the flaw lead during the summer and fall of 1985. Evidence of the degree of

eastward drift which occurs in M'Clure Strait can be found with old ice floe "A" of Figure 5.4. This floe, imaged on February 5, 1986, in central M'Clure Strait (Figure 5.4), is identifiable on the SAR imagery of December 7 and 8, 1986 (Figure 5.3), in western Viscount Melville Sound. This illustrates the extent of flushing of old ice from M'Clure Strait that can occur, even in a year of below average ice reduction and movement such as 1986, since the floe moved 95 nautical miles during the season. Therefore, since central M'Clure Strait receives the highest accumulation of freezing degree days (FDD) and the lowest accumulation of melting degree days (MDD) of the Parry Channel (see Section 3.3.2), the first year ice which forms in the flaw lead will likely survive the melt season in most years and will subsequently drift eastward during the following break-up season to become second year ice, (as of October 1), in eastern M'Clure Strait. In the following break-up year this ice will continue to move further eastward into Viscount Melville Sound to become third year ice as of the following October 1. This ice will be replaced, in central M'Clure Strait, with additional second year ice from the flaw lead. Strewn throughout this younger old ice will be some very old giant old ice floes (estimated at about 15 percent of area) which had invaded M'Clure Strait from the Arctic Ocean. Clearly, this is highly speculative and more detailed analysis is required to confirm such a pattern. The possible occurrence of younger forms of old ice in M'Clure Strait may be significant to the navigation of very large and powerful icebreakers such as the proposed Canadian Polar 8.

4. The SAR and satellite imagery Figure 5.4 also show the characteristics of sub-regime 8W, western M'Clure Strait. The imagery illustrates how the western segment of the ice cover of M'Clure Strait is pulled toward the Beaufort Sea gyre which results in the creation of the flaw lead in central M'Clure Strait.

5. The relatively level first year ice regime of Prince of Wales Strait (sub-regime 6W) with low concentration of old ice is evident on the SAR of Figure 5.4. Of particular note is the lack of any movement of old ice from eastern M'Clure Strait into Prince of Wales Strait during the winter.

5.2.4 Summary Characteristics of the Ice Sub-Regimes of the Western Parry Channel

In this section, the ice characteristics of each of the nine western Parry Channel sub-regimes will be summarized. Frequent references to Figures 5.1, 5.3 and 5.4 as well as Chapters 4 and 3 will be made in this analysis.

Sub-Regime 1W - Western Barrow

a) Location

This sub-regime occupies northern and central area of western Barrow Strait west of Young and Lowther Islands and east of an arching line joining the southwestern tip of Bathurst Island southeastward to Young Island. (see Figure 5.1).

b) Prominent Physical Characteristics

The prominent physical characteristic of this sub-regime is the broad shoal of shallow water extending southward from the southern coast of Bathurst Island. It is speculated, in this thesis, that the unique ice characteristics of this sub-regime stem from the shoaling (and, consequent intensifying) of the west flowing Atlantic tide from central Barrow Strait across the shallow bathymetry of this sub-regime.

c) Distinguishing Ice Characteristics

This sub-regime is characterized by having the highest ice mobility and one of the lowest incidences of old ice occurrence of the western Parry Channel. Fracturing is rapid from east to west, usually over one or two days in early August, and terminates with an ice edge joining Bathurst and Russell Islands. This frac-

ture is aided by an earlier fracture along the south coast of Bathurst Island in the area of the shallow bathymetry in this sub-regime. This early fracture along the south shore of Bathurst Island was illustrated by a NOAA satellite image of Figure 4.9. It is speculated here that this early fracture may well be the result of vertical stresses placed on the ice cover by the shoaling of the Atlantic tide along the shallow bathymetry in this area.

Ice reduction is slower in this sub-regime after fracture than in central Barrow Strait to the east or Viscount Melville Sound to the west. Open water with strips and patches of drift ice develops across the northern section of this sub-regime by early September.

The onset of freeze-up begins by the second week of September with the development of young ice. A major distinguishing characteristic of this ice regime is the tendency for this area to remain mobile much later into the winter than the south side of Barrow Strait or Viscount Melville Sound. This can be clearly seen from an analysis of the NOAA satellite image in Figure 5.3. As noted above, this extended mobility is likely due to the breaching of the Atlantic tide across central Barrow Strait into this region.

The damming of the slow, east moving ice behind Garrett, Lowther, and Young Islands during the fall creates a moderate to high degree of ridging in the developing first year ice of the region and this is visible on the SAR of Figure 5.3.

Old ice rarely exceeds concentrations of one to three tenths in this sub-regime and occurs in late August and early September when south winds, typical of the late summer, occasionally drive old ice northward from southern Barrow Strait (sub-regime 3W). The persistence of north-west winds throughout the remainder of the year likely prevents the influx of high old ice concentrations into this sub-regime.

Sub-Regime 2W - Northern Viscount Melville

a) Location

This sub-regime occupies the northern section of Viscount Melville Sound and the southern half of Byam and Austin Channels.

b) Prominent Physical Characteristics

The occurrence of slightly warmer surface water temperatures (Fissel *et al.* 1984) along with slightly higher and more regular tides in the area compared to the central and southern section of Viscount Melville Sound (Forrester 1983) may influence the ice of this sub-regime.

c) Distinguishing Ice Characteristics

The distinguishing ice characteristics of this ice regime are the early and extensive development of open water after fracture in early August and the low concentration of old ice throughout the year. The combination of low lying land mass to the north with prevailing north west winds are clearly a contributing factor to the persistence of first year ice with little to no old ice in this area. However, the rapid development of open water south of Melville Island in early August (as illustrated in a NOAA satellite image in Figure 4.13) occurs during a period of winds from variable directions. Therefore, there must be an oceanographic anomaly of warmer temperatures in this area which contributes to the persistently favourable ice conditions in this area.

Old ice will occasionally invade this area from the south (sub-regime 3W) blown north by southerly winds in the August and September. Old ice in high concentrations will occur in approximately 40 percent of years in the eastern segment of this sub-regime in Byam and Austin Channels as a result of the movement of old ice southward as a result of the fracture of an ice bridge in Byam Martin Channel (sub-regime 5W) in the months of September and October.

Sub-Regime 3W - Viscount Melville - Eastern M'Clure

a) Location

This sub-regime is the largest identified in this study for the Parry Channel. It spans from the southern part of western Barrow Strait, west of Russell Island, across central and southern Viscount Melville Sound to eastern M'Clure Strait east of a line adjoining Cape Vesey Hamilton, Banks Island, to Cape Russell, Melville Island.

b) Prominent Physical Characteristics

The prominent physical characteristic of this sub-regime is the complete lack of any discernible surface water currents. In addition, tides are very low in this region.

c) Distinguishing Ice Characteristics

The persistence of high old ice concentrations (in excess of 7 tenths) from season to season and year to year is the primary characteristic of this sub-regime. Export of old ice to the east is limited by the damming of ice against Russell, Hamilton and Young Islands in central Barrow Strait. To the south, export is prevented by the persistence of an ice plug in M'Clintock Channel (sub-regime 4W) and of Prince of Wales, Victoria and Banks Island. The occurrence of high old ice concentration in this sub-regime is evident on the SAR of Figures 5.3 and 5.4.

The fracture of this sub-regime occurs both from Barrow Strait to the east and M'Clure Strait to the west. Fracturing from the east occurs in early August, in most years, as a pattern of large cross-channel fractures radiate westward from Barrow Strait into Viscount Melville Sound. A large fracture occurs in most years spanning from Stefansson Island diagonally northwestward across Viscount Melville Sound to the Dundas Peninsula, Melville Island. This fracture separates the two sections of this sub-regime 3Wa to the east from 3Wb to the west. The section of 3Wb is the last area to fracture for the Parry Channel with much of the

fracturing occurring from M'Clure Strait to the west. Unlike the northern part of Viscount Melville Sound, (sub-regime 2W), there is little ice reduction after fracture in this sub-regime.

The extent of old ice in this sub-regime provides a significant barrier to navigation for the Parry Channel. The alternate route for the Parry Channel, through Prince of Wales Strait, is congested with high old ice concentration in the western segment of this sub-regime in Viscount Melville Sound which has provided great difficulties to many of the passages of vessels through the area in the late summer, minimum ice condition (de Bastiani 1986).

There is a south-eastward movement of old ice from central M'Clure Strait to Viscount Melville Sound from the late summer to the early winter. It is likely that most of the movement occurs from September to November when winds prevail from the north-west as wind is clearly the only consistent driving force of the ice of this sub-regime (Verrall *et al.* 1974). Much of the old ice found in this sub-regime is formed in situ in the Parry Channel, either in central M'Clure Strait (sub-regime 7W) or in this sub-regime. Lesser amounts of old ice originate from the Arctic Ocean through M'Clure Strait. A small amount of the old ice found in the eastern segment of the ice regime originates from Byam Martin Channel to the north. Based on the analysis of old ice growth and movement, described previously in the SAR analysis of Figures 5.3 and 5.4 as well as below for sub-regime 7W, much of the old ice in this sub-regime is likely three or more years old.

The ice of this sub-regime will remain unconsolidated until mid-November at which time a clear transition occurs between a relatively lead dominated regime to a compact regime with few leads. This transition occurs as wind is no longer able to shift and mobilize the thickening ice cover as it dams and consolidates to the east behind the ice edge in western Barrow Strait. This compactness likely results in a high degree of ridging in the first year ice around the old ice floes and this is evident on the SAR of Figure 5.4, particularly in southern Viscount

Melville Sound west of Stefansson Island. Consolidation usually follows shortly after compaction in late November or early December.

Sub-Regime 4W - M'Clintock

a) Location

This sub-regime occupies M'Clintock Channel south of an arching line joining Stefansson Island eastward to Prince of Wales Island.

b) Prominent Physical Characteristics

There does not appear to be any prominent physical environment characteristic that typifies M'Clintock Channel. Like Viscount Melville Sound to the north, there is little to no surface water current within the Channel. It has been documented that the Atlantic tide, moving westward from Barrow Strait turns south in M'Clintock Channel but it is very small and is likely insignificant to the ice of the Channel.

c) Distinguishing Ice Characteristics

The distinguishing ice characteristic of this Channel is the perennial plug of old ice which persists from year to year. The persistence of this plug of old ice prevents the wind driven southward drift of ice from Viscount Melville Sound contributing to the persistence of old ice in sub-regime 3W.

The break-up of M'Clintock Channel in late July is initiated from Victoria Strait to the south and terminates with an ice edge between Stefansson Island and Prince of Wales Island. At no time during the thirteen years of this study did the fracture of M'Clintock Channel extend northward into Viscount Melville Sound despite the fact that fracture in M'Clintock Channel usually occurs one to three days earlier.

Ice reduction is minimal after fracture in M'Clintock Channel. The lack of any discernible water currents in the Channel, combined with the constricted basin to the south prevent the export of ice and contributes to the persistence of very

high concentrations of old ice even in years of much above average ice reduction in the region. Viscount Melville Sound (sub-regime 3W) consolidates earlier in the winter than M'Clintock Channel which leaves an ice bridge from Stefansson Island to Prince of Wales Island in most winters. The consolidation of M'Clintock Channel follows later in the winter.

Sub-Regime 5W - Southern Byam Martin

a) Location

This sub-regime occupies the southern portion of Byam Martin Channel north of Byam Martin Island.

b) Prominent Physical Characteristics

The prominent physical characteristics of this sub-regime is the moderate south flowing current, of 10 nautical miles per day, through Byam Martin Channel from the Prince Gustaf Adalf Sea and the Arctic Ocean to the north. This current is the strongest current found in the otherwise placid western Parry Channel ice regime.

c) Distinguishing Ice Characteristics

The distinguishing ice characteristic of this sub-regime, as it affects the Parry Channel to the south, is the movement of high concentrations of old ice in vast to giant floe sizes in many years southward from the Sverdrup Basin into Viscount Melville Sound.

The fracturing of this sub-regime occurs in two stages. The first is the fracturing of southern Byam Martin Channel from Austin and Byam Channels northward to a line joining Ile Vanier to Melville Island (sub-regime 5Wa) in the first week of August in most years. The fracturing to the north of this line into sub-regime 5Wb occurs in years of average or above average break-up which has represented 54 percent of the past 13 years.

The fracture of this sub-regime presents a paradox in terms of ice conditions

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that could impact navigation in the Parry Channel. In years of warmer than average temperatures and consequent above average break-up, results in the fracture of sub-regime 5Wb and the consequent influx of high old ice concentration into Viscount Melville Sound. Conversely, in years of below average temperatures and consequent limited ice reduction, sub-regime 5Wb does not fracture, resulting in an area clear of old ice across northern Viscount Melville Sound (sub-regime 2W).

▲ The influence of this sub-regime on the Parry Channel is evident from an analysis of the SAR imagery of Figures 5.3 and 5.4. Figure 5.3 illustrates conditions in a below average ice reduction year when the ice bridge in Byam Martin Channel did not fracture leaving level first year ice in sub-regimes 5Wa and 2W. Figure 5.4 illustrate conditions in an above average year when this sub-regime fractured leaving high concentrations of old ice in sub-regimes 5Wa and 2W.

Sub-Regime 6W - Prince of Wales

a) Location

This sub-regime occupies all of Prince of Wales Strait between Banks and Victoria Islands.

b) Prominent Physical Characteristics

There are two prominent physical characteristics of this sub-regime. The first is the narrow width of the passage of eight nautical miles. The second feature is the counter currents of a weak south flowing current along the west side of the Channel from Viscount Melville Sound and a weak north flowing current along the east side from Amundsen Gulf to the south.

c) Distinguishing Ice Characteristics

The timing and pattern of break-up and consolidation of this sub-regime varies little from year to year and does not appear to be affected by events in Viscount Melville Sound to the north or Amundsen Gulf to the south. It is likely that the narrow width of the passage results in the early consolidation due to the rapid

development of shore fast ice across the Strait in the fall. The development of shore melt by solar radiation in the spring likely mobilizes the ice cover which causes fracture. Consequently, the influences of variation in temperatures and wind over the season which would affect a large water body such as Viscount Melville Sound to the north or Amundsen Gulf to the south would have a much reduced impact on a constricted regime such as Prince of Wales Strait.

The major influence of Viscount Melville Sound to the north on this sub-regime in the occasional wind driven movement of old ice into the Strait in the late summer and early fall. The floe size of the old ice tends to be small but may pose an impediment to navigation due to the narrow width of the Strait which makes evasion difficult. However, the movement of old ice from Viscount Melville Sound reduces in the fall as freeze-up begins and the congealing ice cover no longer flows into the Strait.

Sub-Regime 7W - Central M'Clure

a) Location

This sub-regime occupies central M'Clure Strait and is bounded to the east by a line joining Cape Vesey Hamilton, Banks Island to Eglington Island and to the west by a line joining Cape Wrottesley, Banks Island to Cape Mecham, Prince Patrick Island.

b) Prominent Physical Characteristics

There are few oceanographic measurements from this sub-regime but it appears, based on the analysis of ice movement from this study, that the western edge of this sub-regime represents the eastern most penetration of the gyral currents and tides from the Beaufort Sea into the Parry Channel.

c) Distinguishing Ice Characteristics

This sub-regime forms an important birth place for old ice within the Parry Channel. As described previously in Section 4.3, freeze-up event 12 and in the SAR

analysis of Section 5.2.3, a large first year ice flaw lead forms each winter in central M'Clure Strait. The first year ice of the flaw lead usually survives the summer melt season and drifts eastward to the eastern side of this sub-regime in the late summer and fall to become second year ice as of October 1. Consequently this sub-regime is characterized as having predominantly first year ice in the western half and predominantly second year ice to the east each year. This second year ice drifts the following year into sub-regime 3W to the east to be replaced by more second year ice from the flaw lead to the west.

Sub-Regime 8W - Western M'Clure

a) Location

This sub-regime occupies the western end of M'Clure Strait west of sub-regime 7W and east of a line joining Cape Prince Alfred, Banks Island, to Griffith Point, Prince Patrick Island.

b) Prominent Physical Characteristics

Like much of the western Parry Channel, there is little oceanographic data collected for the western segment of M'Clure Strait. Based on the behaviour of the ice of this area, it is likely that the Beaufort Sea surface current gyre, which flows southwestward across the western perimeter of the Arctic Archipelago, penetrates into western M'Clure Strait along the north side south of Prince Patrick Island before moving cross channel in central M'Clure Strait to exit on the south side along the north shore of Banks Island.

c) Distinguishing Ice Characteristics

The behaviour of the ice of this sub-regime appeared, during the period of this study, to be strongly influenced by the Beaufort Sea. This sub-regime is the first to fracture and the last to consolidate for the western Parry Channel. The pattern of both the spring fracture as well as the winter consolidation closely mirrors the pattern observed for Amundsen Gulf (sub-regime 9W) to the south.

It is speculated, in this thesis, that the current and tidal forces of the Beaufort Sea, although small compared to Baffin Bay to the east, penetrate into these sub-regimes and causes the early fracture and delayed consolidation of western M'Clure Strait and Amundsen Gulf.

The ice of western M'Clure Strait fractures in the first week of July in most years. The ice will remain in western M'Clure Strait throughout the summer and fall with a slight drift to the south-west toward the Beaufort Sea. Under strong westerly or north-westerly winds, giant old ice floes from the Beaufort Sea will be blowing, on occasion, into this sub-regime and subsequently further eastward into the Parry Channel. The slight south-westerly drift of the ice of this sub-regime contributes to the formation of the central M'Clure Strait flaw lead (sub-regime 7W) and potentially high ice pressures along the north shore of Banks Island. The tendency for the ice of this sub-regime to drift to the west is evident in the satellite image of Figure 4.7 presented in the previous chapter and the SAR and satellite images of Figure 5.4 previously.

Sub-Regime 9W - Amundsen

a) Location

Although this area is not part of the Parry Channel, it is included in this analysis so that the entire waterway from Baffin Bay to the Beaufort Sea may be described in this thesis. This sub-regime occupies the waterbody of Amundsen Gulf.

b) Prominent Physical Characteristics

A weak counter clockwise flowing current circulates through Amundsen Gulf from the Beaufort Sea.

c) Distinguishing Ice Characteristics

This sub-regime shares a similar pattern of break-up and freeze-up with sub-regime 8W mentioned above. This sub-regime is a first year ice regime that com-

pletely clears to open water each summer. Fracture is initiated from the Beaufort Sea to the west in late June with consolidation not occurring until late into the winter with the Gulf remaining unconsolidated in approximately twenty percent of winters. Old ice occurs in very low concentrations; with the primary source being small floes in strips and patches drifting southward from Prince of Wales Strait in the late summer and fall.

Chapter 6

Conclusions and Recommendations

In this thesis, the ice regimes of the Parry Channel have been defined. Ice characteristics of the Channel were determined from NOAA VHRR and AVHRR satellite imagery and A.E.S. ice charts for the period January, 1974, to December, 1986. Additional characteristics were also derived from recently collected synthetic aperture radar (SAR) imagery. Recorded ice behaviour patterns and data on the oceanographic and atmospheric environment were compared to aid in the delineation of the ice regime and sub-regimes of the Parry Channel. Speculations on the causes of these ice regimes were also made.

This chapter summarizes the major findings of this thesis and makes recommendations for further study.

6.1 Conclusions and Recommendations on Method

The NOAA satellite and SAR imagery were the most valuable data sources used in the analysis. Although the thirteen year period of coverage was considered adequate for this study, an analysis covering a longer period of satellite data might reveal additional patterns for the Parry Channel. The SAR imagery proved to be valuable in the detection of many ice features, such as the distribution of old ice,

not easily determined from other sources. However, only three years of SAR data covering the Parry Channel were available at the time of writing. Therefore, the following recommendation is made:

Recommendation 1.0

It is recommended that the continued collection of SAR imagery of the entire Parry Channel be encouraged, and that each additional year of NOAA satellite imagery stored in the Ice Climatology archives be analysed along with the SAR to update the ice regime characteristics of the Parry Channel.

6.2 Conclusions and Recommendations on Ice Regimes

Two ice regimes in the Parry Channel have been identified: The eastern Parry Channel ice regime, which comprises the waterways and adjoining channels of northwestern Baffin Bay, Lancaster Sound, as well as eastern and central Barrow Strait and the western Parry Channel ice regime, which comprises the waterways and adjoining channels of western Barrow Strait, Viscount Melville Sound and M'Clure Strait. It has been found in this study that these two ice regimes each have markedly different characteristics and it is these differences which serve to separate these areas as distinct regimes. The difference between the two regimes were found to be as follows:

1. The eastern Parry Channel is dominated by a seasonal and highly mobile first year ice cover that does not survive the summer melt season, while the western Parry Channel is dominated by a stagnant predominantly old ice cover with a significant amount of the first year ice surviving the melt season.

2. Old ice is transitory in the fall and early winter in the eastern Parry Channel but is perennial in the western Parry Channel. The western Parry Channel ice regime is a significant source region of old ice for the Parry Channel.
3. Fracture of the ice cover is usually complete by late July in the eastern Parry Channel but is delayed until mid-August for the western Parry Channel.
4. Consolidation is usually complete by early December with little to no variation in extent in the western Parry Channel but is not complete until early March for the eastern Parry Channel where a wide degree of variation in extent occurs from no consolidation to complete consolidation.

The highly dynamic conditions of the eastern Parry Channel contrasting with the stagnant conditions of the western Parry Channel is likely the result of the domination of the eastern Parry Channel by the Atlantic Ocean water mass and the corresponding domination of the western Parry Channel by the Arctic Ocean water mass. The influences of the Atlantic Ocean water mass penetrate as far west as central Barrow Strait bringing warmer and more saline waters, stronger surface water currents and higher tidal ranges than experienced in the western portion of the Channel. This warmer Atlantic water mass modifies the climatic environment providing more melting degree days and fewer freezing degree days accumulations and more variable winds than experienced in the western Parry Channel. The influences of the Arctic Ocean water mass penetrates eastward to western Barrow Strait bringing colder and less saline sea water, weak to non-existent surface water currents and a very low tidal range. The colder water mass also modifies the climatic environment, providing colder temperatures and more persistent north-west prevailing winds than found in the eastern Parry Channel. Therefore, it is speculated here as a result of the analysis of this thesis that it is the separation of waters of Atlantic Ocean influence from those of Arctic Ocean influence that likely causes the marked differences in ice regime characteristics between the eastern and

western Parry Channel.

Although numerous patterns of ice behaviour have been identified in this study, most of the attempted explanations of the factors causing these patterns were necessarily speculative in nature. This is due to the lack of detailed information available in the open literature on the physical environment of the Parry Channel. There is a particular lack of information dealing specifically with the effect of oceanographic and atmospheric variables on sea ice growth and distribution within the Parry Channel. The following recommendation is made:

Recommendation 2.0

It is recommended that further oceanographic studies of the Parry Channel be continued and expanded, particularly studies relating to the distribution of the Atlantic and Arctic Ocean water masses within the Channel. Concurrent with these oceanographic studies, detailed sea ice studies, using data collected both on the ice surface and remotely, should be undertaken so the correlation of observed ice behaviour may be made to measured oceanographic features.

6.3 Conclusions and Recommendations on Ice Sub-Regimes

The interaction of the water masses within the Parry Channel likely is the cause of the many regional variations in the pattern of break-up, movement and freeze-up. These regional patterns have been identified in this study as ice sub-regimes for the Parry Channel with eleven sub-regimes identified for the eastern Parry Channel and nine for the western Parry Channel.

The convergence of the south flowing Canadian Current from Nares Strait with the south-east flowing current from Jones Sound through Lady Ann Strait and the

east flowing current from Lancaster Sound appears to be a significant factor to the creation of three sub-regimes for the eastern Parry Channel. The formation of first year ice and the movement of old ice in these converging currents in the late fall and early winter create high ice pressures and ice ridging north of Bylot Island which delineates the area of sub-regime 1E (north-western Baffin). The current flowing south-eastward from Jones Sound into the eastern entrance to Lancaster Sound appears to be the main transport mechanism of old ice from northern Baffin Bay into Lancaster Sound in the late fall. However, the deflection of old ice out of this current, possibly by thickening first year ice, prevents the further influx of old ice into Lancaster Sound by the early winter. This feature delineates sub-regime 2E (Lady Ann).

Dis-ordered surface water currents in eastern Lancaster Sound likely is the cause of the observed plugging of the east-flowing ice in eastern Lancaster Sound during the mid-winter. It has been observed that this plugging often precedes consolidation of Lancaster Sound and likely contributes to heavy first year ice ridging over the winter. In addition, these dis-ordered currents may also result in the delayed fracture of this area in the spring. It is this pattern of ice plugging that delineates sub-regime 3E in eastern Lancaster Sound. Since the existence of heavily ridged first year ice in the spring and high old ice concentrations in the late fall and early winter have proven to be serious impediments to navigation in eastern Lancaster Sound, the following recommendation is made:

Recommendation 3.0

It is recommended that the interaction of the surface water currents with the sea ice environment of eastern Lancaster Sound be studied in detail.

The movement and shoaling of tidal energies through Lancaster Sound into northern Prince Regent Inlet, Barrow Strait and Wellington Channel may be important in influencing the timing and pattern of break-up and freeze-up in the east-

ern Parry Channel. Areas where tidal shoaling may have an important influence include northern Prince Regent Inlet and western Lancaster Sound (sub-regime 5E), as well as central (sub-regime 6E) and western (sub-regime 1W) Barrow Strait. If tidal energies are indeed important to break-up and freeze-up then the prediction of these events may be possible as tidal forces are one of the few environmental variables that can be predicted with a high level of reliability. Therefore, the following recommendation is made:

Recommendation 4.0

The influences of tidal energies on the break-up and freeze-up process in the eastern Parry Channel should be studied. These investigations should study the possible correlation of spring and neap tides to increased or decreased tendencies toward consolidation or fracture. In addition, tidal gauges should be placed at critical locations in western Lancaster Sound and Barrow Strait to measure the degree of tidal height variation which may occur in these areas.

Unlike the highly dynamic eastern Parry Channel, where the boundaries between the various water current and tidal areas serve to delineate sub-regimes, the calm stagnant waters of the western Parry Channel make wind patterns and the weak Beaufort Sea gyral current important variables in the delineation of sub-regimes. The western Parry Channel is dominated by a large area of old ice in southern Viscount Melville Sound and eastern M'Clure Strait (sub-regime 3W). The pattern of interaction of the two sub-regimes of central and western M'Clure Strait (sub-regimes 7W and 8W) with Viscount Melville Sound to the east gives important clues to the origin of a large component of the old ice field that predominates in the western Parry Channel ice regime. The westward drift of the ice of western M'Clure Strait (sub-regime 8W) towards the Beaufort Sea in the mid-winter period creates a large first year ice flaw lead each winter. It appears that this first year ice survives the summer melt season to become second year ice

the following fall. Due to the prevailing north-west winds in the western Parry Channel, this second year ice drifts eastward into central and eastern M'Clure Strait by late fall of each year. It is speculated here that the youngest old ice (i.e., second or third year) to be found in the Parry Channel occurs in central and eastern M'Clure Strait with the age increasing eastward into Viscount Melville Sound. The following recommendation is made:

Recommendation 5.0

A detailed study should be undertaken in M'Clure Strait to document the dynamic interaction of old ice creation and transport to Viscount Melville Sound. Such a program should include remote sensing experiments using SAR imagery to document the movement of specific ice floes from season to season and year to year. Additional surface based studies should be undertaken to document the extent of second year ice within M'Clure Strait. The existence of a high concentration of second year ice in M'Clure Strait may prove significant to navigation for large and powerful icebreakers such as the planned Polar 8, which may be more able to navigate through second year ice than older ice.

Much work has been undertaken, in the past few years, on the development of more capable icebreaking vessels and ice navigation systems using remotely sensed data to extend the navigation season within the Parry Channel. However, experience has shown that improved icebreaking performance and remotely sensed data alone aboard a vessel does not extend the navigation season. What is also needed is a thorough understanding of the ice environment the vessel will face (Gorman 1987(b)). In this thesis, the ice environment of the Parry Channel has been described to aid in this understanding. Numerous patterns of ice behaviour were identified that appeared to correlate closely with documented patterns of currents, tides and winds. The combination of these correlated characteristics were used to define the ice regimes and sub-regimes of the Parry Channel. It is

It is hoped, that with this base understanding of the ice regime mechanism of the Parry Channel, more effective use of ice information onboard vessels navigating in these waters may be realized.

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