A Reconstruction of Summer Sea Ice Conditions in the Labrador Sea Using Hudson's Bay Company Ships' Log-Books, 1751 to 1870

by

John Vincent Teillet

A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of

Master of Arts
in
The Department of Geography

Winnipeg, Manitoba

ISBN 0-315-47970-1

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ABSTRACT

The sailing ships' log-books contained in the Hudson's Bay Company Archives were used to reconstruct summer sea ice conditions in the Labrador Sea from 1751 to 1870. This reconstruction involved the development of an ice severity index, derived from a content analysis of the word roots and phrases in the ice descriptions, and the comparison of historic encounters with the presence of ice in the same sector in 1965.

The ice severity index obtained for the Labrador Sea did not demonstrate a significant relationship with other ice severity indices derived for Hudson Strait and Hudson Bay. The ice severity index displayed some similarities to ice severity derived for other regions of the Labrador Sea.

A highly significant volcanic signal was found in the ice severity index indicating a relationship between volcanic dust and the atmospheric circulation responsible for late ice retreat in the Labrador Sea.

The number of icebergs sighted each year was also estimated for the period 1751 to 1870.

ACKNOWLEDGEMENTS

I would like to thank the members of my committee, Dr. W. Last, Dr. D.W. Moodie, and in particular, I wish to sincerely thank my thesis adviser, Dr. A.J.W. Catchpole for his constructive criticism and assistance in editing this thesis.

I also acknowledge Mrs. Shirlee Smith, keeper of the Hudson's Bay Company Archives, and the Hudson's Bay Company for its permission to consult and quote from its archives.

Financial support for this thesis was received from the Canadian Climate Centre of the Atmospheric Environment Service.

Thanks also to the following graduate students in the Geography Department: Gary Doige, Danny Blair, Marci Faurer and Irene Hanuta.

Finally, special thanks to my mother, Kathleen Teillet, whose support, both emotional and financial, and editing skills made this research possible, and it is to her that this thesis is dedicated.

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Chapter 1: Introduction, Previous Research and Plan of Thesis

It is not easy for the average Canadian to acquire a balanced appreciation of the immensity and significance of the tangle of islands, peninsulas, straits and inland seas that comprise our arctic and subarctic territory. From our perspective Canada is an elongated country spanning five time zones, connecting two oceans, and its cities and agricultural land are flung in a narrow belt along the United States border. Our customary view of the country fails to grasp the fact that the linear distance from Lake Erie to the northernmost point of Ellesmere Island at Alert is approximately the same as that from Vancouver to Halifax, or that the coast of Baffin Island is encountered at roughly the midpoint between Lake Erie and Alert. Off the southeast coast of Baffin Island lies the Labrador Sea, an area that even today is considered remote.

The remoteness of the north is also reflected in the relative paucity of scientific knowledge of the region. One manifestation of this, that is relevant to the subject of this thesis, concerns our knowledge of sea ice conditions in Hudson Bay and its approaches through Hudson Strait and the Labrador Sea. The Labrador Sea has had centuries of fishing, whaling and exploration, and together with Hudson Strait and Hudson Bay these waters have a long commercial history as a sailing route for vessels engaged in trade between Europe and harbours on Hudson Bay. Ships have plied this route since the founding of the Hudson's Bay Company in 1668 and the modern shipping era dates for the establishment of the port of Churchill in 1929. Despite this long history, knowledge of ice conditions in Hudson Bay was so deficient in the mid twentieth century that Burbidge (1951) stated:

> Until 1948 little was known about the area of ice in the central waters of Hudson Bay in winter. Ice was known to form around the edges but reports by local residents and explorers all expressed the opinion that the central parts of Hudson Bay remained as open water throughout the winter. This was also the opinion of many circles in the United States ; the authoritative *Ice Atlas of the Northern Hemisphere* (1946) shows only a narrow coastal fringe of ice.

It is surprising that only four decades have elapsed since it first became known that this great inland sea freezes over in winter. Equally surprising is that the evidence provided by Burbidge consisted not of direct observations made during scientific aircraft surveillance but rather of indirect climatological evidence. Prior to the January freeze-up, polar continental air is significantly warmed during its passage across Hudson Bay, presumably due to contact with open water. From January through March the absence of this warming indicates contact with a virtually unbroken ice cover.

Burbidge's (1951) findings were, however, published immediately before the commencement, in the early 1950s, of systematic aerial ice reconnaissance in the Canadian arctic and subarctic. By the late 1960s satellite observations became available for the whole polar basin. These technological innovations provided the means for the scientific study of sea ice while recent economic and political forces provided impetus to these studies. Among the most important of these were the energy crisis of the 1970s which pushed the search for energy resources to the high arctic and the realization by Canadians of the arctic archipelago's strategic importance. In the postwar decades the arctic occupied a position of great strategic importance with regard to the military interests of the great powers. Late in this period an awakening of Canadian concern with its sovereignty in the arctic further stimulated scientific research in general and ice surveillance in particular. This has culminated in current plans by the Canadian government to strengthen its navy and increase naval patrols as a means of asserting sovereignty in the arctic archipelago.

Despite these developments the period of the sea ice record remains brief. The primary sources of sea ice information in Hudson Bay, Hudson Strait and the Labrador Sea are weekly maps of ice margins in *Ice Summary and Analysis: Hudson Bay and Approaches* published annually from 1964 through 1973 by Ice

Forecasting Central of Environment Canada. The same information is available for the period since 1973 in unpublished maps prepared by Ice Forecasting Central. Two major secondary sources present the ice information observed since 1964: *Ice Atlas: Canadian Arctic Waterways* (Markham, 1981) and *Ice Atlas: Hudson Bay and Approaches* (Markham, 1988). These sources are a basis for studying spatial patterns of ice information and dispersal, seasonal ice regimes and year to year fluctuations during the last two decades. However, the modern ice record provides no information that can be used in the study of sea ice variations during recent decades and centuries. The only recourse available for the study of long term variations in sea ice is to use the indirect evidence which is primarily contained in written historical sources.

The primary objective of this study is to use the sea ice descriptions contained in the log-books of the Hudson's Bay Company (HBC), to reconstruct summer sea ice conditions in the western portion of the Labrador Sea for the period 1751 to 1870. This research is similar in several respects to that done by Catchpole and Halpin (1987). The objectives and sources of the two studies are the same and the method used to derive the indices also has some affinities with that applied by Catchpole and Halpin (1987). The ice index is compared with other historic sea ice indices, and tested for the presence of a volcanic signal.

1.1 Previous Research

Although the most direct source of historical climatic information is instrumental records, these records do not exist for many areas and where they are available they are often restricted to the recent past. To obtain information before the period of instrumental measurements and scientific surveillance, proxy records of climate must be used. Proxy records are derived from analyses of climatic dependent variables. In his study of the proxy evidence of climatic change in the Quaternary, Bradley (1985) identified historical evidence as one of the four major categories which include also ice core, geological and biological evidence. The fundamental limitation of the historical evidence is the brevity of the period of time in which it is available. However, the strengths of historical evidence lie in the accuracy with which it can be dated and the high resolution of the information it yields. Only ice core and tree ring data compare in quality with the historical evidence in terms of accuracy of dating and resolution (Bradley, 1985, p.3-9).

A general review of paleoclimatic research based on historic evidence is far beyond the scope of this thesis. This review will focus upon three aspects of the use of written historical evidence for climatic reconstruction:

1) studies based on sailing ships' log-books;
2) studies based on both the post journals and sailing ships' log-books in the Hudson's Bay Company Archives (HBCA) in the Provincial Archives of Manitoba (PAM);
3) studies of sea ice conditions in the Labrador Sea.

As early as 1855 the value of ships' log-books in scientific studies was realized: "Every ship that navigates the high seas with these ... logs on board may henceforth be regarded as a floating observatory" (Maury, 1855). Until recently, however, these sources were poorly exploited. Oliver and Kington (1970) used ships' log-books with land station data to produce synoptic weather charts of Western Europe for a number of years in the 1780s. Landsberg (1980) observed that: "a particularly useful source, often meticulously kept, is the log-book of a vessel". These are valuable historic sources because these officers, whether naval or merchant, were instructed to record all manner of details concerning their ships in the log-books. The following is an example of the official directives given to naval officers early in the eighteenth century:

> He [the Captain or Commander] is, from the Time of his going on board, to keep a Journal, according to the Form set down ... and to be careful to note therein all Occurrences, viz. Place where the Ship is at Noon; Changes of Wind and Weather; Salutes, with the Reasons thereof; Remarks on unknown Places; and in general, every Circumstance that concerns the Ship, her Stores and Provisions.
> (Oliver and Kington, 1970)

A reason why log-books have seldom been used as historical climatic sources is that: "much of the detail in ships' log-books is difficult to utilize when it comes to monthly, or longer, periods of climatic reconstruction, for the obvious reason that the period covered at any one locality is a brief one even if the vessel is at port" (Oliver and Kington, 1970). However, a collection of log-books is a potentially valuable source of information about *climatic change* if the ships followed roughly the same route and traveled at roughly the same time of year, for a considerable number of years. The collection of log-books in the HBCA meets these criteria since they were written on ships that followed a prescribed route in mid to late summer for a period of 120 years. In the studies conducted here and by Faurer (1981), Catchpole and Faurer (1983), and Catchpole and Halpin (1987), the ships' log-books in the HBCA were available for Hudson Bay and its approaches through Hudson Strait and the Labrador Sea and provided an indication of the prevailing ice clearing conditions for the 120 year period from 1751 to 1870.

The post journals in the HBCA contain both direct instrumental weather observations and also proxy evidence of climatic conditions. The instrumental observations are primarily of air temperature and, less frequently, surface pressure. The distributions of these observations, instruments and observing routines have been examined by Ball (1983b) and by Wilson (1983, 1985a and 1985b). These researchers developed procedures for correcting the primary observations for inconsistencies in instrumental design and exposure. The proxy evidence in these sources has been used for two general types of climatic reconstruction. The phenological studies have examined seasonal changes by studying dates of first occurrences of river break-up and freeze-up (Moodie and Catchpole, 1975), rainfall and thunder in spring, and snowfall and frost in fall (Ball, 1982). The second approach to the use of proxy evidence has enumerated the frequencies of occurrence of rainfall, snowfall, thunder, specific wind directions etc. (Ball, 1982) to provide indications of the frequencies of occurrence of specific phenomena within the seasons.

A more immediate background to this research was provided by the analyses of historical sea ice conditions conducted by Faurer (1981), Catchpole and Faurer (1983), Catchpole and Halpin (1987), and Catchpole and Hanuta (unpublished manuscript). These studies were also based on the HBC supply ships' log-books. Faurer's (1981) and Catchpole and Faurer's (1983) analysis derived indices of annual summer sea ice severity in Hudson Strait. This analysis was based on the relationship between the duration of the passage through Hudson Strait and ice severity, but did not analyze the descriptions of ice given in the log-books in detail. Catchpole and Halpin's (1987) study of sea ice conditions in eastern Hudson Bay proved to be a useful source because its methodology was applicable, with some modifications, to the ice descriptions in the Labrador Sea.

Few studies have concentrated on sea ice conditions in the Labrador Sea, either historically or at the present day. These include studies by Crane (1978), Sowden and Geddes (1980), Markham (1981 and 1988), and Newell (1983). Each of these relied on a common primary source of information on recent sea ice conditions. Ice Forecasting Central of the Atmospheric Environment Service published weekly, or biweekly, maps showing the spatial distribution of ice conditions classified according to age and concentration, from 1964 to 1973. This information is still available, although unpublished, for the period since 1973. Sowden and Geddes (1980) used these sources to construct a series of weekly maps showing the maximum and minimum ice limits for the period 1964 to 1979 and the median ice limit for the period 1964 to 1973. The ice limits were based on only ten or 15 years of data, but because of the lack of ice information in Hudson Bay and its approaches these limits have been used to represent present day normal and present day extremes. Crane (1978) used the information compiled by Ice Forecasting Central in his analysis of summer ice dispersal, winter ice formation, and the relevant synoptic atmospheric patterns in the Labrador Sea. Crane identified two distinct patterns of ice retreat, termed early and late, and these are discussed in more detail in Chapter 2 and Chapter 7.

Newell's (1979, 1983) research was of particular relevance to this thesis. Newell concentrated on the eastern Canadian arctic, and he reconstructed both modern and historical ice conditions. Newell (1983) used historical evidence from the Moravian missions in Labrador to establish ice conditions in the nineteenth century in the Labrador Sea. In the western part of the Labrador Sea, his sources mainly provided information between 55°N and 59°N. His ice information for north of 59° was from West Greenland sources compiled by Speerschneider (1931). Thus the research in this thesis was adjacent geographically and had very little overlap. There was, however, a large overlap in time period. Although the first mission was established at Nain in 1770, with Okak established in 1776, and Hopedale in 1786, most of Newell's data were from 1800 to 1900. There was a temporal overlap with this research from 1800 to 1870, a total of 50 years. The information derived from the HBCA put together with the information Newell obtained from the Moravian missions gave each set of data a measure of validity. From this a measure of the ice conditions in the western end of the Labrador Sea in the nineteenth century was established.

1.2 Plan of Thesis

Chapter 2 describes the routes and sailing routine of the HBC supply ships and it also defines the study area used in this thesis. The chapter also examines the modern ice conditions observed in the Labrador Sea at the time of the year when the sailing ships made their crossing. The objective of this is to provide background information on the ice conditions that the sailing ships would encounter if they sailed today.

Chapter 3 discusses the HBCA as a data source. The log-books are analyzed in terms of their period of record, numbers, format and contents of the individual log-page, and how information was retrieved from them.

Chapter 4 concentrates on the ability of the HBC officers to locate their ships while at sea. Navigational accuracy is tested and a method of correcting obvious errors is introduced to establish a network of marine sectors in which to locate the ships.

Chapter 5 is an analysis of the word roots and phrases contained in the ice descriptions. These word roots and phrases are coded, using content analysis, to obtain an index of summer sea ice severity in the Labrador Sea.

In Chapter 6 the interpretation of the results involves a comparison of the index obtained in Chapter 5 with other historic sea ice indices from Hudson Bay, Hudson Strait, and the Labrador Sea.

Chapter 7 examines the relationship between volcanic dust and sea ice severity. A significant volcanic signal is observed in the index of summer sea ice severity obtained for the Labrador Sea.

Chapter 8 contains a discussion of icebergs, including the notation used by the HBC, and an attempt is made to provide an annual estimate of icebergs from 1751 to 1870.

Chapter 9 summarizes the results of the study and contains some concluding remarks.

Chapter 2: The HBC Supply Ships

2.1 Sailing Route & Study Area

One of the reasons the data from the ships' logs are very useful is that in each of the 117 years the ships followed the same general route across the Atlantic Ocean. Figure 2.1 shows the usual route of the ships across the Labrador Sea, while Figure 2.2 has the routes of two specific examples, 1835 and 1836. In both figures it is obvious that the HBC crews gave Cape Farewell, Greenland a wide berth. They did this for two reasons. Firstly to avoid ice and secondly because they were unsure of the exact location of Cape Farewell. Chappell mentions this in his narrative. "According to some charts, we considered ourselves this day to be in the longitude of Cape Farewell in Greenland. Nothing can exceed the uncertainty that prevails in almost every chart and book of navigation, respecting the longitude of the Cape in question" (Chappell, 1817, p.34). Once past Cape Farewell the ships headed northwest until they were at about the same latitude as Resolution Island. When they were within sight of Resolution Island the ships entered Hudson Strait by passing close to the south of Cape Resolution. The reasons for this route will become apparent when ice conditions and ocean currents are examined.

Figure 2.1: Typical Route Through the Labrador Sea

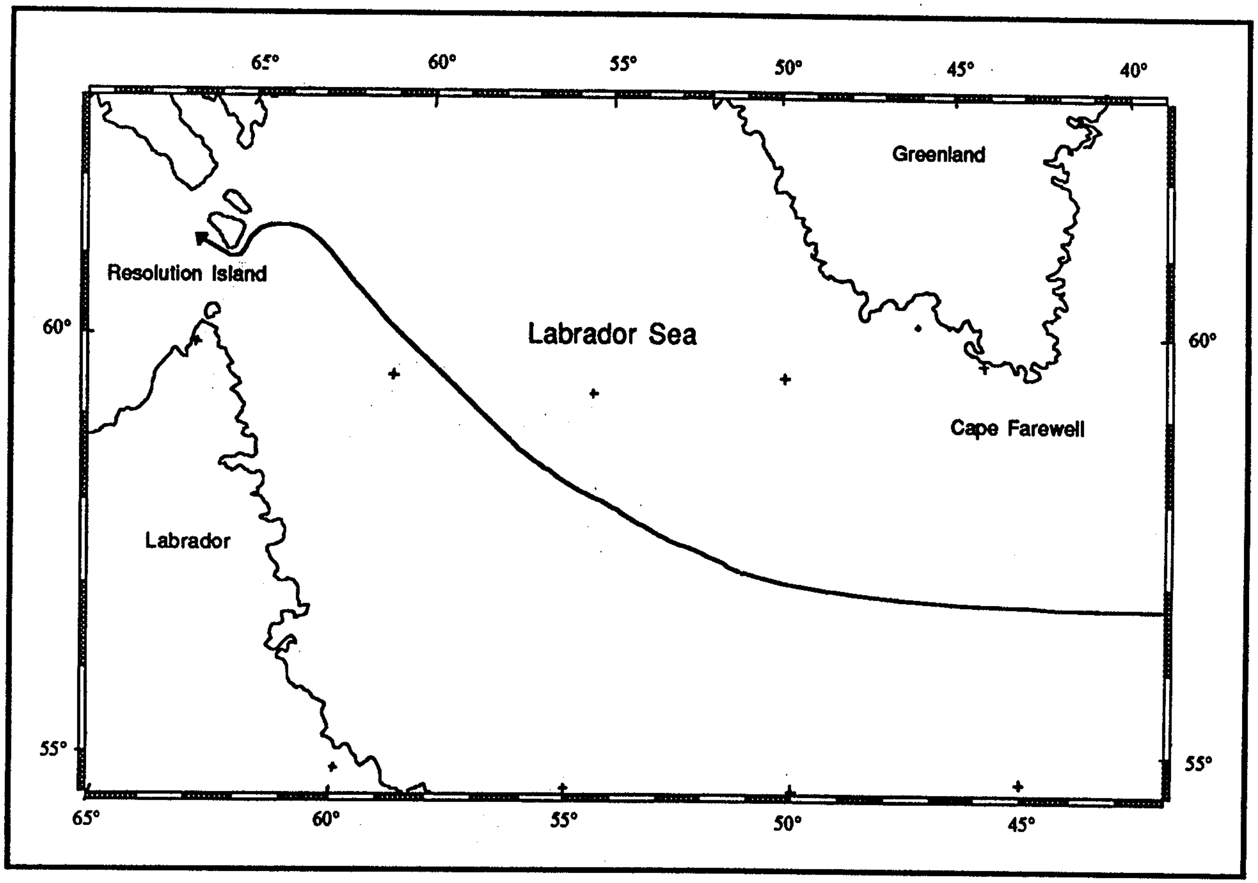


Figure 2.2: Routes Sailed by the HBC Ships in 1835 and 1836

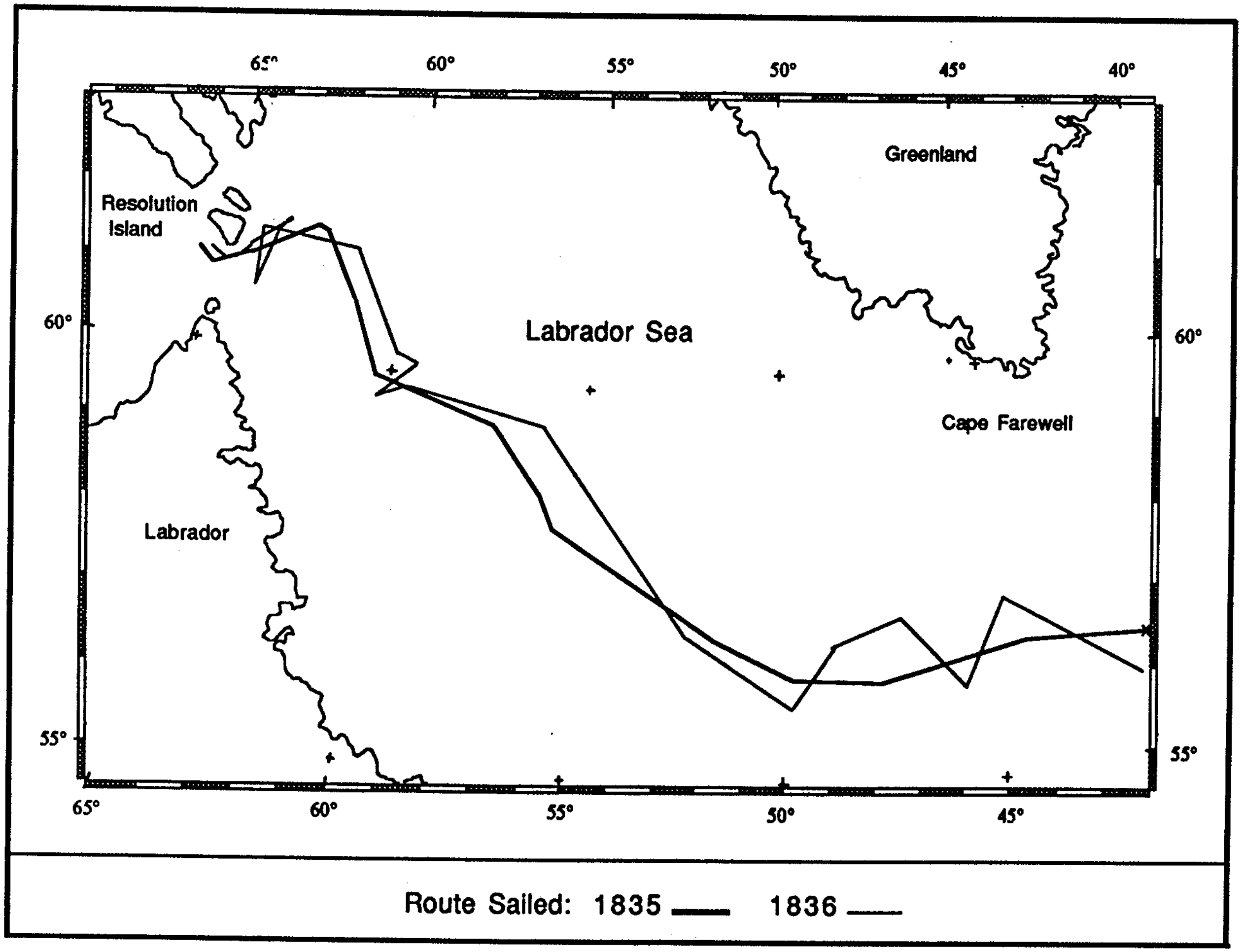
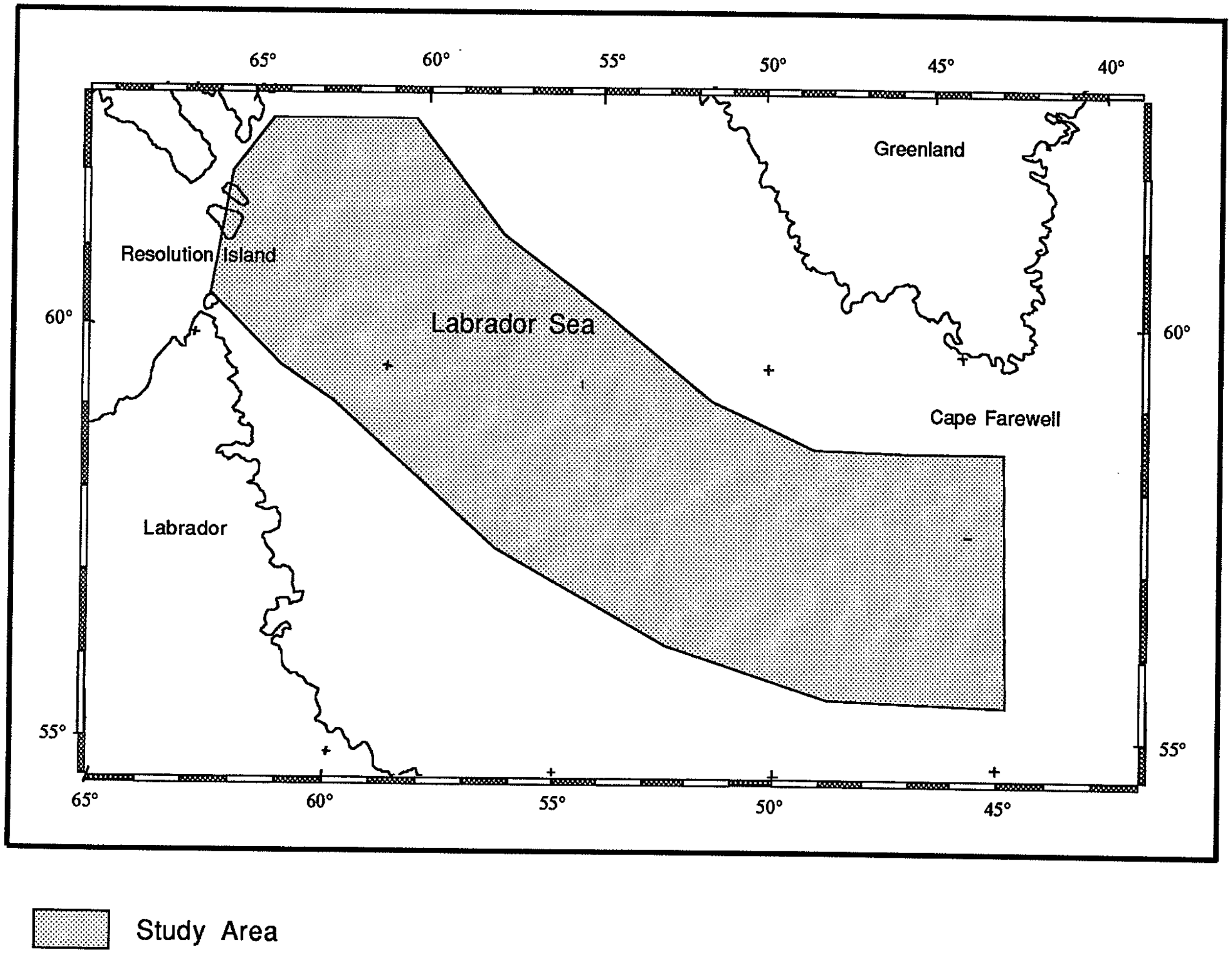


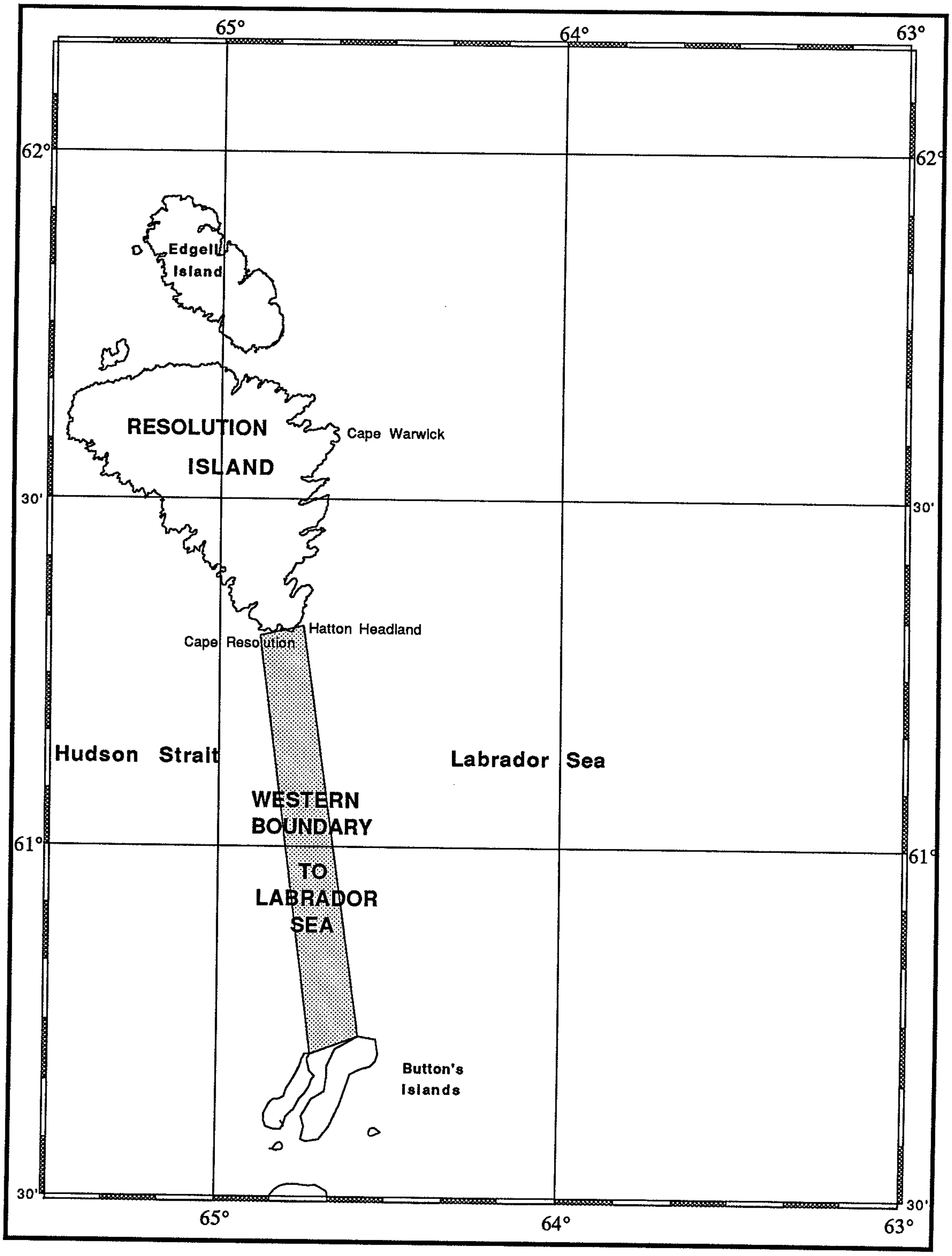
Figure 2.3: Study Area: The Labrador Sea



The area of study for this research is the Labrador Sea, shaded in Figure 2.3. This is a broad area spanning about 180 miles (nautical miles are used throughout this historical study) in width but the ships usually followed a fairly straight route and did not range over a very large north-south area in the Labrador Sea in any one year. The eastern boundary is the west coast of Greenland and the longitude of Cape Farewell in the Atlantic Ocean. Precision in determining this boundary is not a major concern as ice was very seldom seen in this area. In fact, almost all pack ice sightings were in the western portion of the Labrador Sea. The western boundary to the study area is the entrance to Hudson Strait which is enlarged in Figure 2.4. The entrance to Hudson Strait is a natural boundary and the sailors considered that the rounding of Cape Resolution marked the end of their Atlantic crossing and the end of the first leg of their trip. The following excerpts from two different voyages demonstrate how the crew considered passing Cape Resolution as the entrance to Hudson Strait:

> 10 am Rounding Cape Resolution and at 10 AM I judge we were abreast of it.
> noon About 10 AM I think we entered Hudson's Straits.
> *(HBCA, PAM, King George II log-book, August 7, 1776, C.1/380.)*
>
> At 9 past the Cape and entered the Strait.
> *(HBCA, PAM, King George III log-book, July 20, 1787, C.1/390.)*

Figure 2.4: The Western Boundary of the Study Area



If the log-keeper did not actually specify when the ship entered Hudson Strait or passed Cape Resolution, the time of entry would be approximated from the bearings of the landmarks. For example, if Cape Resolution was recorded as having a south-east bearing with respect to the ship then the ship had passed the Cape and could be considered in Hudson Strait.

In one year, 1753, the ships did not enter Hudson Strait by passing to the south of Cape Resolution. Instead, the HBC ships became embayed in ice and were carried into Hudson Strait north of Resolution Island. The route the ships were forced to take cannot be determined since precise locational information was not given in the log-books on this occasion. The log-book entries from July 26 to July 28, 1753 are given in Figure 2.5, and these demonstrate the helplessness of the crew as the ocean current and ice forced the convoy into Hudson Strait.

It is important to note that Faurer (1981), in her analysis of ice conditions in Hudson Strait, used a different definition of the entrance to Hudson Strait. In her study, the ships were considered to have entered Hudson Strait when the crew reported that they first saw Resolution Island. This means that there is a slight overlap in the areas covered by the two studies. In most cases, this is a minor overlap spanning about one day but, in 1816 the Prince of Wales I did not enter Hudson Strait for 25 days after the crew first sighted Resolution Island.

Figure 2.5: The King George I Log-book, 1753
July 26 to July 28

July 26 Latitude by account: South of 62

2 pm	at a grappling in fast ice
4 am	Saw the Land from South to NNE: by which we are quite Imbayed & in fast Ice still driving on towards the shore, God knows the event. we are not able to do anything, being fast in Ice

July 27

4 pm	driving about NW throu' many Islands in fast Ice
8 pm	the HBay fast to the same piece of Ice
3 am	At 3 was set by the tide and Ice within ten yards of a point of an Island the Ice very rude & close ... we recieve a great many hard squeezes but thank God no damage to the ship at present

July 28

3 pm	at 3 drove so near small island as we could reach it with an Ice trowl. The tide running near four mile an hour recieved a very hard squeeze but did us no damage but did some damage to the HBay. Ruther saw the land SSW: end NNE: which Southern point appears thro' haze to be SW end of Resolution...
12	I find we now drive about west by compass which gives me reason to believe we are now in Hudson's Streights as we cannot see land to the Westwards

(HBCA, PAM, King George I log-book, 1753, C.1/362)

2.2 Sailing Dates of the HBC Ships

Not only did the ships follow the same route year after year but they also sailed at the same time of year. Ice conditions in Hudson Strait dictated the time of year in which the supply ships sailed. Hudson Strait is only open to navigation for a few months in the summer and fall each year. Thus the ships had to traverse Hudson Strait as soon as possible after the ice opened in spring to enable them to deliver provisions to the posts in Hudson Bay, pick up furs, and then return through Hudson Strait before freeze-up. These time constraints ensured that the HBC supply ships crossed the Labrador Sea and entered Hudson Strait at about the same time each year. A statistical analysis of some key dates was applied to ascertain the dates the ships left Britain, the dates they entered Hudson Strait, and the durations of their Atlantic crossing.

a) Date of Departure from Britain

Almost all of the HBC westward voyages originated in London, at Gravesend from which they usually sailed in late May. In 1850 and 1857 they sailed directly from London to North America, but in most other years the ships sailed to Stromness Harbour in the Orkney Islands (107 out of 117 years), to take on additional supplies, passengers, and crew. Chappell discusses the reason the HBC crews stopped at the Orkney Islands in his narrative: "[A]s it is from [Orkney] that they derive all necessary

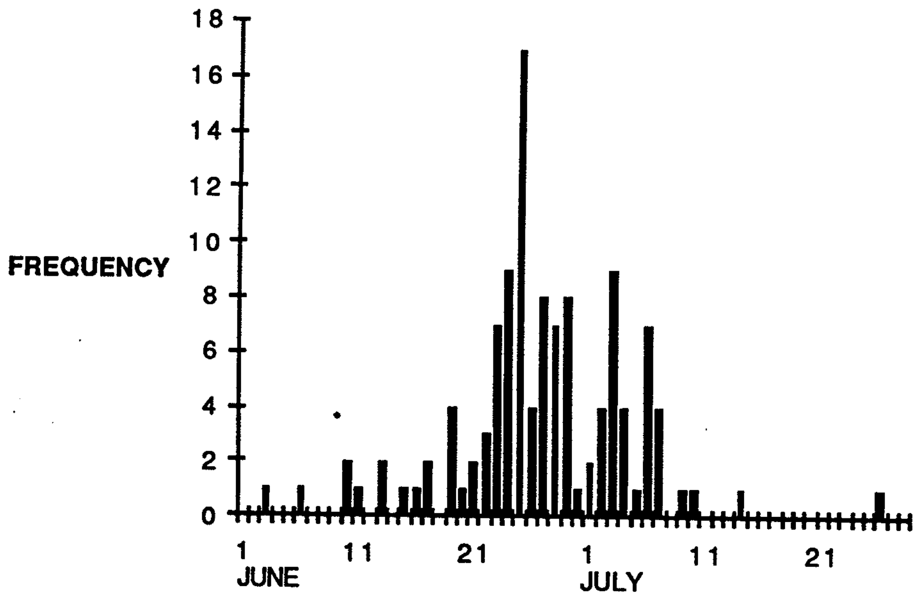


Figure 2.6: Dates of Departure of HBC Ships from the British Isles

supplies of poultry, beef, vegetables, and even men, to fit them for so long a voyage" (Chappell, 1817, p.13). In three years (1765, 1766, and 1767) the HBC used Kinsale Harbour in Ireland, and in five other years Stornaway Harbour in the Isle of Lewis was used as the last port. As the stay at these ports was variable, the *departure date* was taken as the date when the convoy actually left its final port in the British Isles and embarked on its westward crossing of the Atlantic Ocean.

For statistical analysis, all dates were converted to numbered days after May 31. Thus June 1 is day 1, June 20 is day 20, July 1 is day 31, etc. Table 2.1 shows that the earliest departure date was June 3, the latest was July 26, and the mean date of departure was June 27. Although there is a range of 53 days the actual departure dates were clustered about the mean. This is shown graphically in Figure 2.6 and evaluated by the standard deviation in Table 2.1.

Table 2.1: Summary of Departure Dates, Dates of Entry into Hudson Strait, and Durations of the Atlantic Crossing

	Mean	Standard Deviation*	Earliest/ Shortest	Latest/ Longest
Departure	June 27	7.5	June 3	July 26
Entry	July 28	10.1	June 23	Sept 6
Duration*	31	6.8	17	54

* in Days

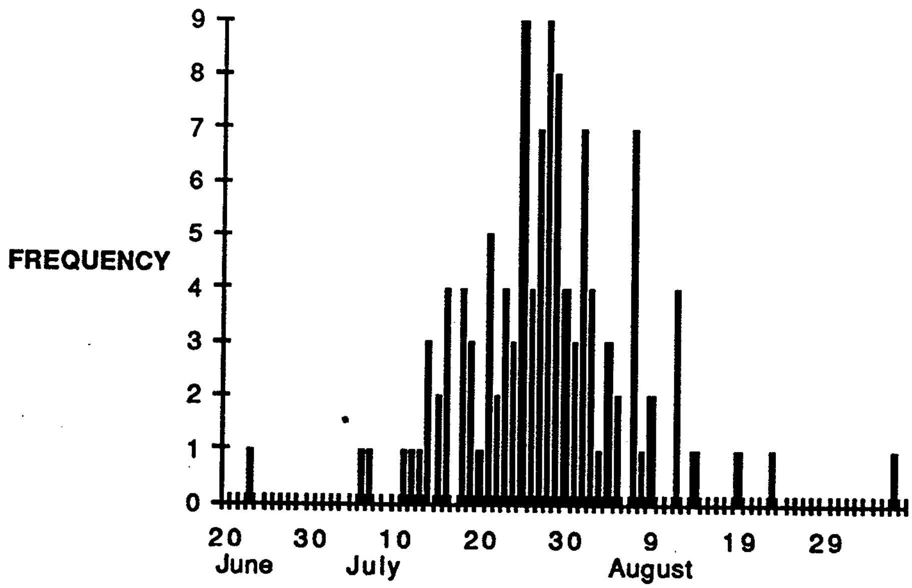


Figure 2.7: Dates of Entry of HBC Ships into Hudson Strait

b) Date of Entry into Hudson Strait (DES)

The point at which the ship left the study area and entered Hudson Strait was recorded using the definition given in Chapter 2.1. The DES was taken as the date on which the ship reached this point. Table 2.1 shows that the earliest DES was June 23, and the latest DES was September 6. The mean DES was July 28 and the extreme range was 75 days. Over 62% of the DES were within a week of the mean and nearly 77% were within 10 days of the mean. The standard deviations in Table 2.1 indicate a greater dispersal from the mean following the Atlantic crossing. Nevertheless, the DES display a clustering about the mean and this is also evident in Figure 2.7.

c) Duration of Atlantic Crossing

Duration of Atlantic crossing in days was obtained by subtracting the departure date from the DES. The range of duration was 37 days with the shortest Atlantic crossing taking only 17 days in 1810, and the longest requiring 54 days in 1816 (Table 2.1). The average trip length was 31 days. Figure 2.8 indicates that the durations are roughly normally distributed and clustered about the mean (standard deviation = 6.8 days).

The last port of departure, dates of departure, dates of entry into Hudson Strait, and durations of the Atlantic crossings are listed by year for all 117 years in Appendix 3.

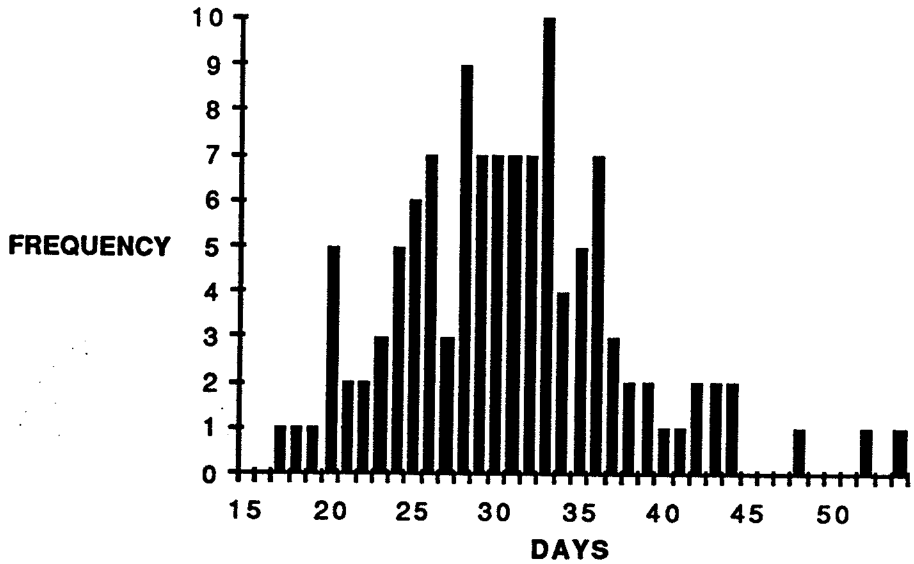


Figure 2.8: Durations of the Atlantic Crossing

2.3 Ice Encountered in the Labrador Sea

It is apparent from Figure 2.7 that the HBC ships usually entered Hudson Strait considerably earlier than the date on which the port of Churchill opens for shipping at the present time. This implies that the policies of the Hudson's Bay Company required their sailing ships to face ice hazards in the Labrador Sea, Hudson Strait, and Hudson Bay which today are considered to be unacceptable insurance risks to modern ocean-going cargo vessels. The Hudson's Bay Company had, of course, no option in this matter. It was essential for its ships to enter Hudson Bay early in the break-up period to ensure a return passage through Hudson Strait before the freeze-up in early winter. The ships' log-books therefore make frequent reference to ice in the Labrador Sea during the westward passage in summer. However, ice was rarely encountered in these waters during the return passage in fall because the pack ice develops earlier in Hudson Strait than in the Labrador Sea. Consequently, the log-books provide information on summer ice dispersal, but not on winter ice formation.

The primary source of information on recent sea ice conditions in the Labrador Sea is *Ice Summary and Analysis: Hudson Bay and Approaches* published by Ice Forecasting Central of the Atmospheric Environment Service. This was published between 1964 and 1973 and it contains weekly, or biweekly, maps showing the spatial distribution of ice conditions classified according to age and concentration. In the period since 1973 there are unpublished manuscript maps showing the same information and prepared by Ice Forecasting Central of the Atmospheric Environment Service.

These sources have been used by Crane (1978) and Sowden and Geddes (1980) in their studies of patterns of summer ice dispersal and winter ice formation in the Labrador Sea and neighbouring waters. The objectives of these studies are related but they differ in important respects. Crane's objectives were to:

1) identify the years in which there were *early* and *late* summer ice dispersal in the Labrador Sea

2) describe how the spatial patterns of ice dispersal differ between the early and late years

3) identify the synoptic atmospheric circulation conditions associated with early and lȧte ice dispersal and formation.

The objectives of Sowden and Geddes' study were much narrower. Their purpose was to construct a series of weekly maps showing the following ice limits:

1) the maximum ice limit defined as the area in which ice was observed in at least one year between 1964 and 1979

2) the minimum ice limit defined as the area in which ice was observed in every year between 1964 and 1979

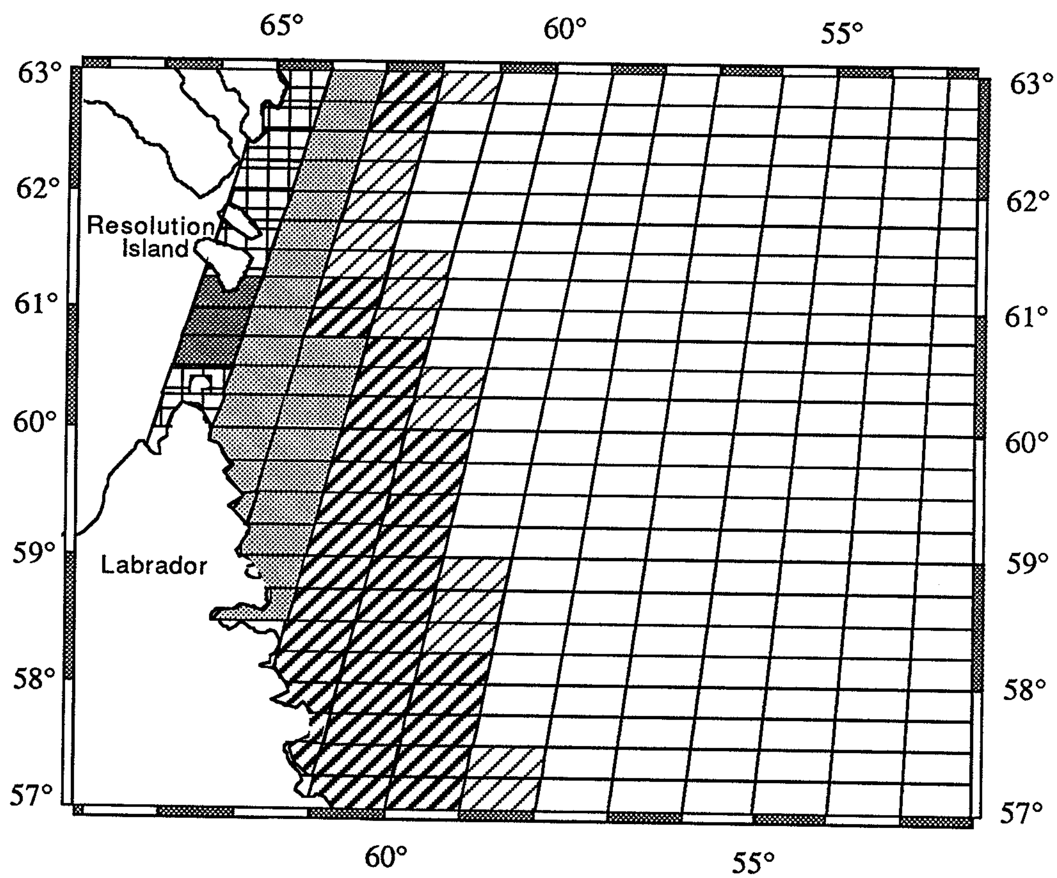
3) the median ice limit defined as the area in which ice was observed in five of the ten years between 1964 and 1973.

Figure 2.9 illustrates the spatial pattern of the median ice limits identified by Sowden & Geddes. This information is presented as chloropleths in a network of sectors, each having dimensions of 1° longitude and 15' latitude (the marine sectors are discussed in Chapter 4). The chloropleths represent the latest date on which ice was observed in five of the ten years between 1964 and 1973. In the path of the HBC ships across the

Labrador Sea this date ranges from May 21 in the eastern portion to July 23 at the entrance to Hudson Strait. This date is close to the mean date of entry into Hudson Strait of July 28. Figure 2.7 shows that the majority of ships had entered the strait after July 23 but a substantial proportion (26%) entered before that date. It is apparent that, *if the HBC ships had sailed under present ice conditions*, they would have encountered significant pack ice in the western part of the Labrador Sea. Given the greater ice severity in the sailing ship period (Wilson, 1985a; Newell, 1979) it is abundantly clear that these ships encountered hazardous pack ice in the Labrador Sea.

Crane's (1978) reconstructions of early and late patterns of summer ice dispersal suggest similar conclusions. Figures 2.10 and 2.11 exemplify the early and late patterns using 1965 and 1973 as examples. In both examples, the ice demonstrated the same general trend of east to west clearing. The eastern approach to Resolution Island cleared first, with the entrance to Hudson Strait opening afterwards. In 1965 open water was encountered in the paths of the ships by May 21 in the eastern portion of the Labrador Sea, and by June 25 at the entrance to Hudson Strait. In 1973 the eastern approach to Resolution Island is not clear until July 16. In both examples the areas around Edgell Island, Button's Islands, and the southern coast of Baffin Island are not ice free until after the entrance to Hudson Strait is open. The entrance itself opens up first in the north, just south of Resolution Island before the southern part around Button's Islands opens. In 1965 the entire entrance to Hudson Strait was clear by July 16 while only the northernmost part of the entrance was clear by that date in 1973. In 1973 ice was observed in the middle of the entrance until August 6, and the entire entrance was not clear of ice until August 20. Ice was also present to the southeast of Resolution Island until August 20. Through a comparison of the route (Figure 2.1) and the late pattern of ice retreat (Figure 2.11) it is apparent that the HBC sailing ships would have avoided the later ice in most years, and the presence of this late ice explains why the crews took a semi-circular route to reach Resolution Island. The major factor influencing ice clearing conditions in this area is the ocean currents, shown in Figure 2.12. The southern part of the entrance to Hudson Strait is influenced by a current coming out of Hudson Strait. Because the ice in Hudson Strait clears after the entrance does, the ocean current functions to remove ice from the strait. This results in a later ice presence in the southern part of the strait entrance, because ice from Hudson Strait is being removed. Even when the HBC crews made their voyages they understood these conditions and attributed them to ocean currents:

Figure 2.9: Median Ice Extent 1964 - 1973



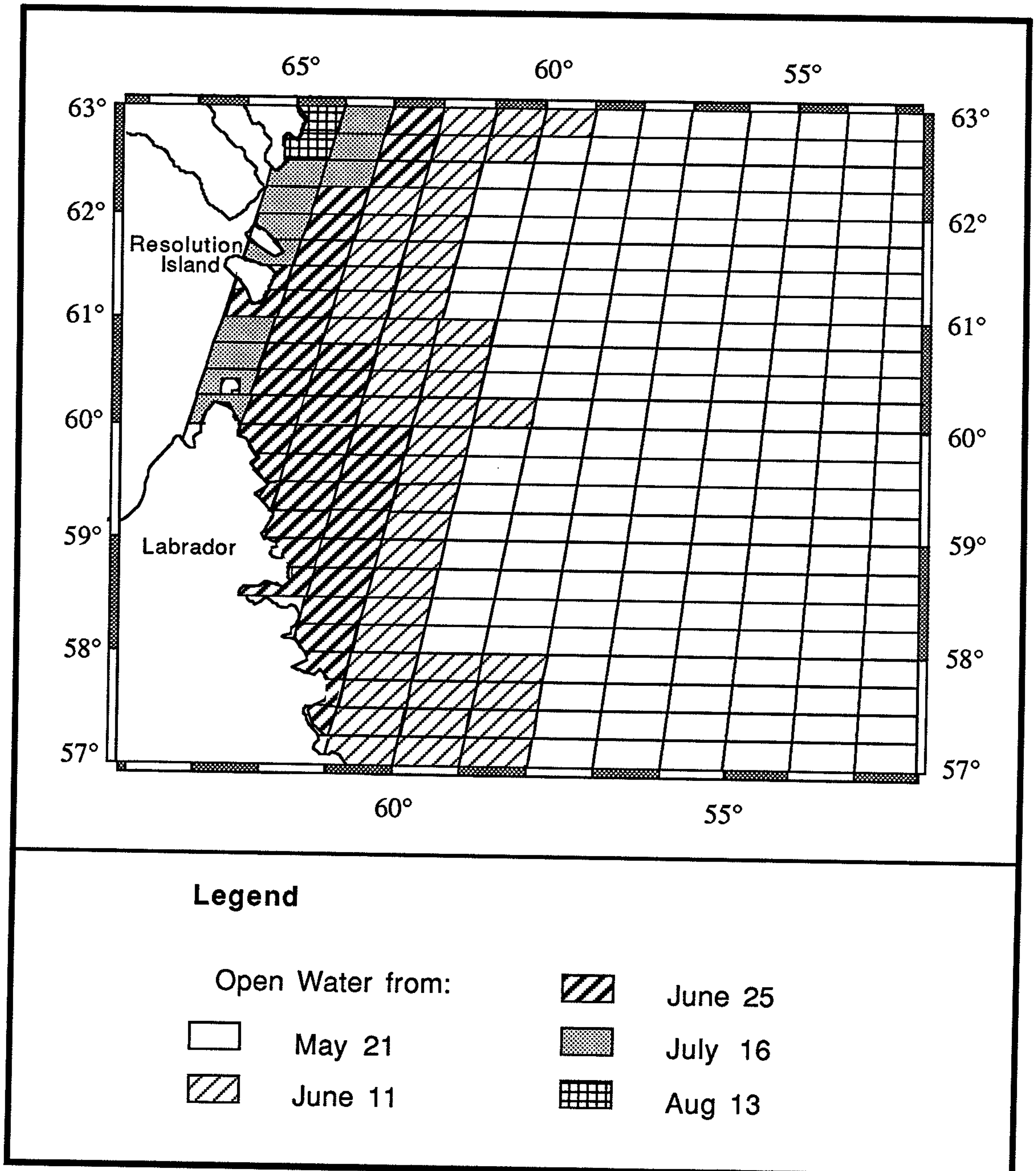
Legend

Latest date on which ice was observed in half of the years between 1964 and 1973:

- May 21
- June 11
- June 25
- July 16
- July 23
- July 30

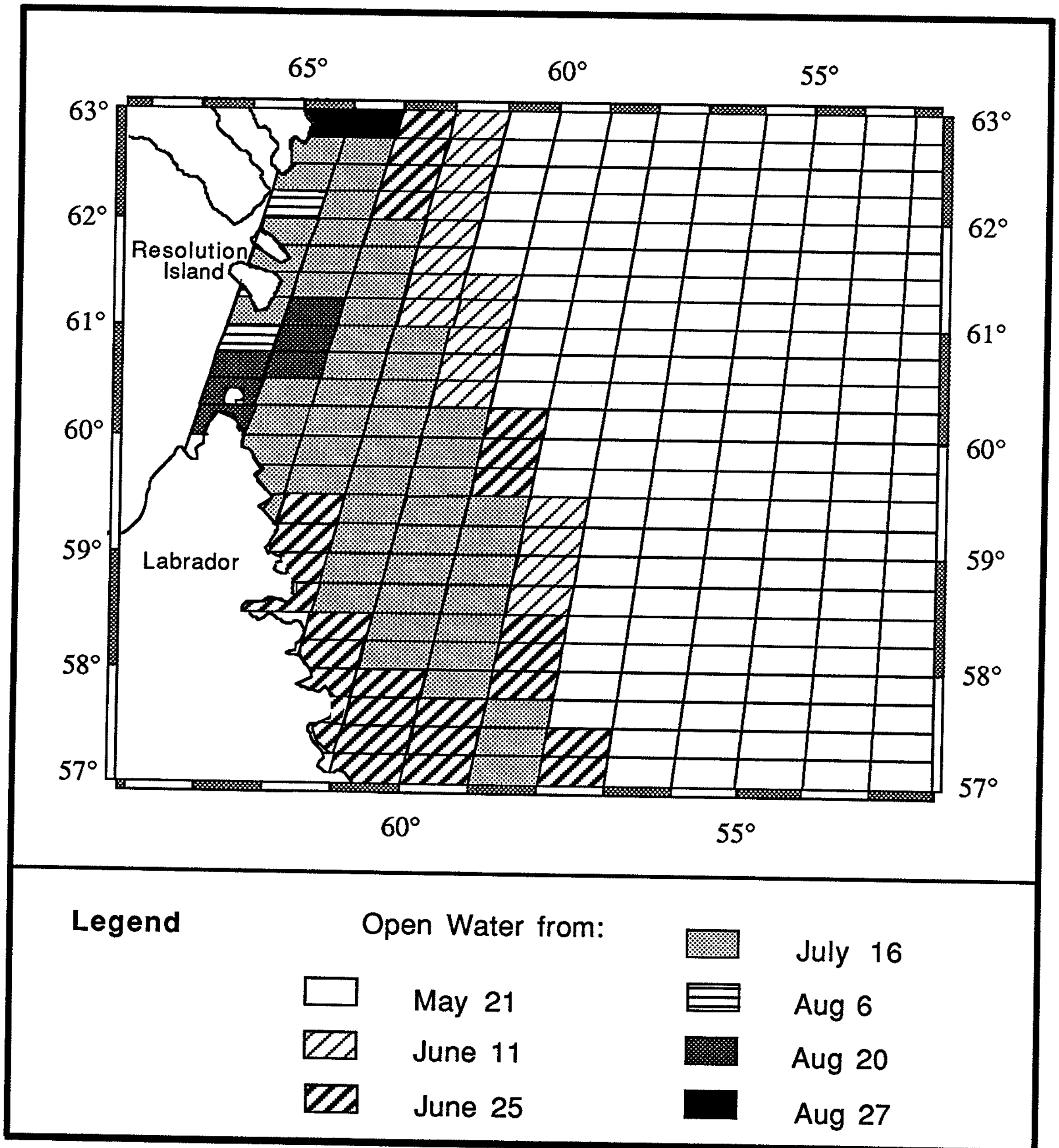
(adapted from Sowden and Geddes, 1980)

Figure 2.10: Early Pattern of Ice Retreat, As illustrated by 1965 Season



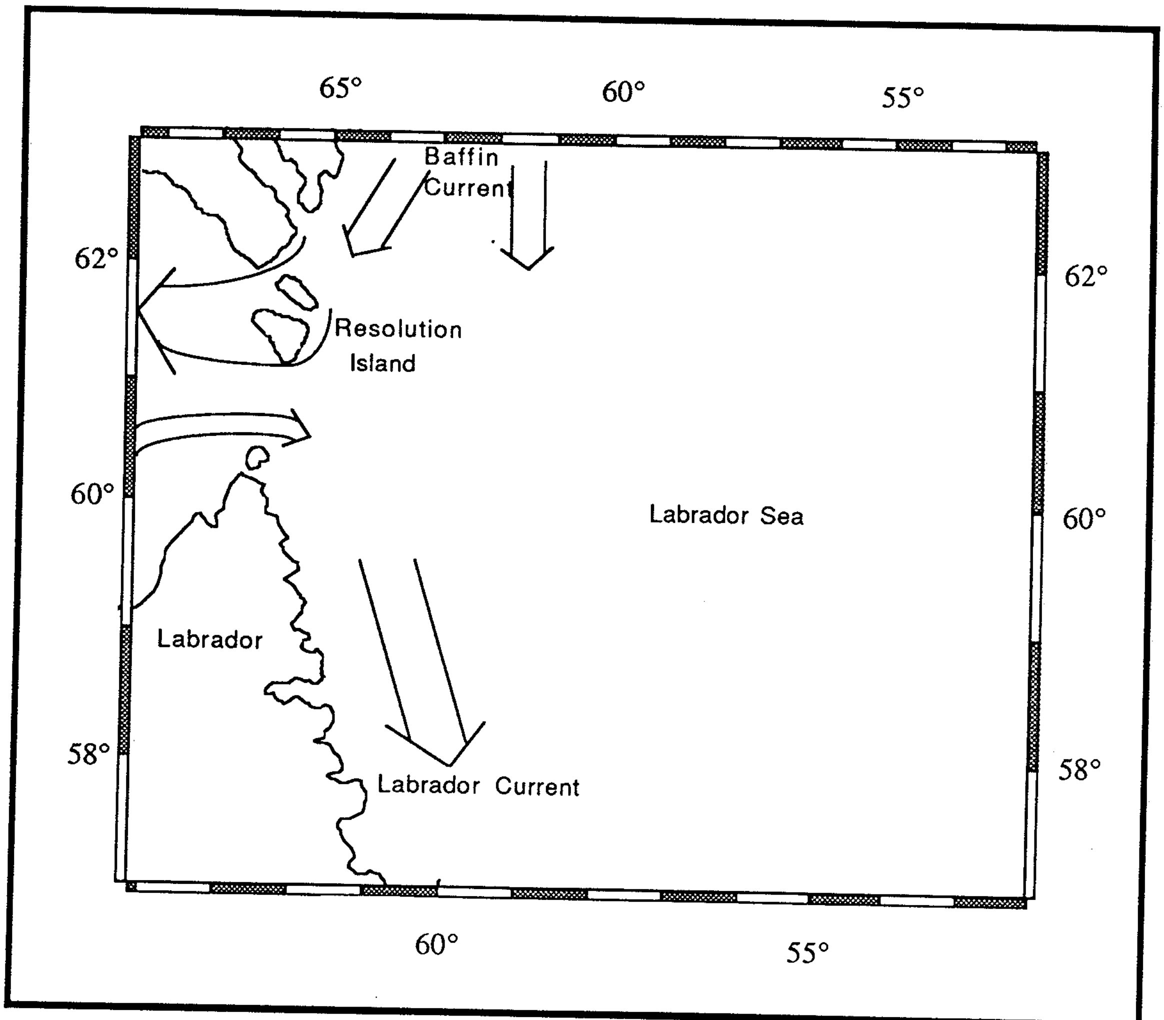
(adapted from Crane, 1978)

**Figure 2.11: Late Pattern of Ice Retreat,
As illustrated by 1973 Season**



(adapted from Crane, 1978)

Figure 2.12: Ocean Currents in the Labrador Sea



(adapted from Cherniawsky and LeBlond, 1987)

> Entering *Hudson's Straits*, it is a necessary precaution to keep close in with the northern shore; as the currents out of *Hudson's* and *Davis' Straits* meet on the south side of the entrance, and carry the ice with great velocity to the southward, along the coast of *Labrador*.
> (Chappell 1817, p.40-41).

The late ice to the southeast of Resolution Island which is observed in 1973 (Figure 2.11), is likely a result of ice coming out of Hudson Strait meeting ice coming south from Davis Strait and backing up along the northern coast of Labrador.

Chapter 3: The Log-Book Record

The HBC Archives in Winnipeg contain an almost complete collection of log-books from HBC ships sailing to Hudson Bay in the period 1751 to 1870. There are log-books for every year with the exception of three years from 1839 to 1841. In most years the ships travelled in flotillas ranging in size from one to five ships, although most often there were two or three ships (Table 3.1). Not only is there a log-book from each of these ships, but on several of the ships more than one officer would keep a log giving a total collection of 485 log-books.

Because of the delicacy and historical value of the log-books, each has been copied onto microfilm. The microfilm copies of the log-books were used for this research because access to the original log-books was restricted. For this research one log-book was selected from each year. The choice of the log-book was based mainly on the legibility and the completeness of the log. Legibility is an obvious criterion as the information contained is useless unless it can be extracted accurately from the log-books. Figure 3.1 is an example of a typical log-page. It is not uncommon for the log-books to be incomplete. Most often the missing information was the locational information given in the noon summary at the bottom of the log-page. As log-books kept aboard the same ship were almost identical in most cases, for the few years in which both complete and legible log-books were unavailable, a second log-book from the same ship was used to complete the locational information.

Table 3.1: HBC Ships Yielding Log-books

Flotilla Size (Ships per Year)	# of Years (frequency)
0	3
1	4
2	46
3	54
4	12
5	2
Total =	316

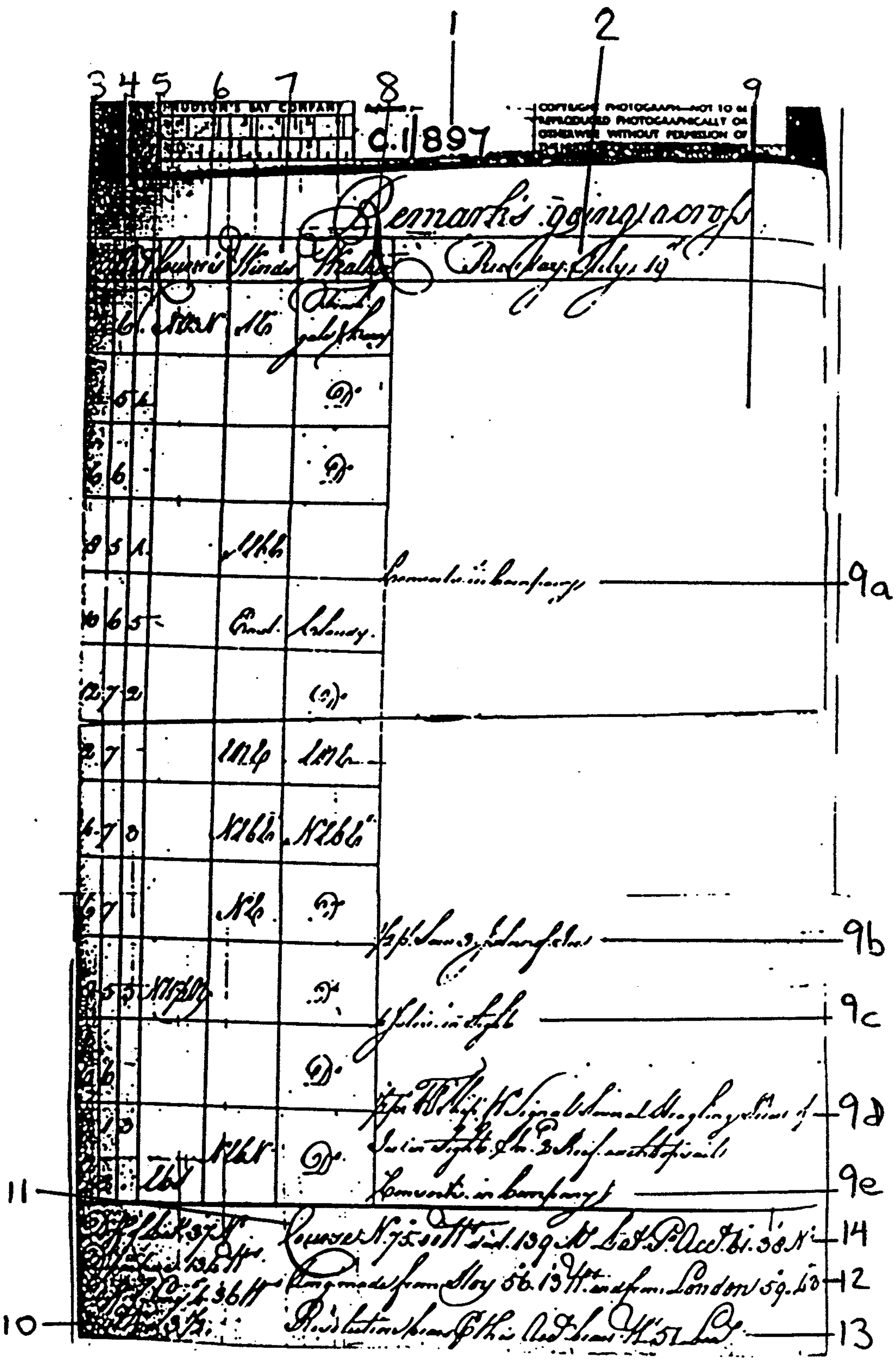
from Catchpole and Moodie (1978)

3.1 Format and Contents of the The Log-Book Page

An advantage of the HBC log-books as sources of ice information is that the log-books were generally kept in a uniform manner throughout this 117 year period. The officers of the HBC were instructed to meticulously record details of their voyages. These details included descriptions of occurrences of ice, the location of landmarks, as well as hourly (or bi-hourly) recordings of course and speed of ship, wind direction, and weather. Undoubtedly an element of subjectivity entered into these descriptions. However, the descriptions in the log-books are probably very representative of the ice conditions encountered by the crews. This becomes evident when studying the log-books and noting their daily progress, and actions taken when ice was encountered.

Figure 3.1 is a photocopy of a microfilm of a typical log-page. Almost all log-pages are organized in this way, ruled into seven columns, with the date on top and a noon summary at the bottom. The following is a description of the main types of information recorded using the log-page in Figure 3.1 as an example. To facilitate this description, the various pieces of information are numbered. The information denoted with an '*' was extracted and used in this research.

Figure 3.1: Sample Log-Book Page



(HBCA, PAM, Prince Rupert III Log-book, July 19, 1774, Folio 17d, C.1/897)

* 1 "C.1/897" This is not part of the original log-page but is the HBCA piece number which was added during the microfilming process. Each log-book has its own piece number used by the HBC Archives as a code for identification.

* 2 "Tuesday: July 19" This was the date on which information in the log-page was recorded, but the first twelve hours are actually the afternoon of July 18, and the next twelve hours are the morning of July 19. This is because the seaman's day extended from noon to noon.

* 3 "H" This column was used to record time, usually in two hour intervals, although sometimes one hour intervals were used.

4 "K" The average speed of the ship, in knots, for the hour or two hour period was entered in this column.

5 "F" Depth of the water in fathoms, when known, was recorded in this column.

6 "Courses" This column was used to record the course direction using a 32 point compass (Appendix 1 explains the 32 point compass). The 2:00 pm entry is NWBN, the 8:00 am entry is

NW1/2N, and the noon entry is EbS. The course was not entered unless there was a change and then the new course was recorded.

7 "Winds" Wind direction was entered in this column.

* 8 "Weather" This column was used for general comments about weather and visibility. In this example the 2:00 pm entry is "fresh gale and hazy", and the 10:00 pm entry is "cloudy". Other typical examples include: "foggy", "fine", "thick", "thick fog". The D° repeated frequently in this column is the log-keeper's symbol for ditto, which of course means that the weather is the same as before.

* 9 The seventh column is the remarks column in which many types of information were recorded. Most ice sightings as well as comments on crew, sails, positions of consorts, and landmark sightings were recorded in this column. Comments 9a to 9e are typical of remarks entered in this column.

9a & 9e "Consorts in Company" This comment was first given at 8 pm and repeated at noon. "Consorts in Company" means that all the ships that were sailing across the Atlantic together were within sight of each other.

* 9b, 9c, & 9d These are typical ice sighting comments and they are transcribed in Figure 3.3.

The noon summary appears at the bottom of the page. This summary contains observations made at noon of the date at the top of the log-page, which in this example was July 19. Most of the information recorded in the noon summary was navigational.

* 10 "Var 3 1/2" This is compass variation. At the latitudes at which the HBC ships were traveling, there is a large difference between true north and magnetic north. The magnetic declination was recorded faithfully during the Atlantic crossing at noon of each day. In this example the 3 1/2 stands for 3 1/2 points west on a 32 point compass, or about 40 degrees. The compass variation ranged from about 3 points (34 degrees) to about 5 points (56 degrees) in the study area.

* 11 "Course N 75.00 W dist. 139 M"

This is a summary of the day's sailing, determined by dead reckoning. The corrected course and distance run were calculated and added to the ship's position from the day before to fix the position of the ship at noon. This new location would be recorded in the log-book as latitude and longitude by account. In this particular example the Prince Rupert traveled 139 nautical miles in a direction 75° north of west over the 24-hour period.

* 12 "Long. made from Hoy 56.13 W and from London 59.43" This is longitude by account, which was determined by course and distance run from yesterday's position. It was not common for the officers to record both longitude from London and longitude from Hoy in the Orkney Islands. In several of the earlier years longitude was recorded from Hoy (3°30 W) rather than London (0°). Hoy was used because it was often the last sighted land until the ships were within sight of Resolution Island. Hoy itself was probably used as it has a distinct landmark described by Chappell as "... immediately opposite to which is the Isle of Hoy, having on it a remarkable high mountain, in shape very like the rock of Gibralter" (Chappell, 1817, p.13). After 1818, longitude was always recorded as longitude from London (Catchpole and Halpin, 1987).

* 13 "Resolution bears [P][1] this Acct. bears W. 51 Lea."

The log-keeper has determined the relative position of Resolution Island according to the ship's accounts. This is entered in the noon comment. In this example the accounts of the ship placed Resolution Island 51 leagues (about 150 nautical miles) to the west. When landmarks became visible their compass bearings and estimated ranges were given in the noon summary.

---

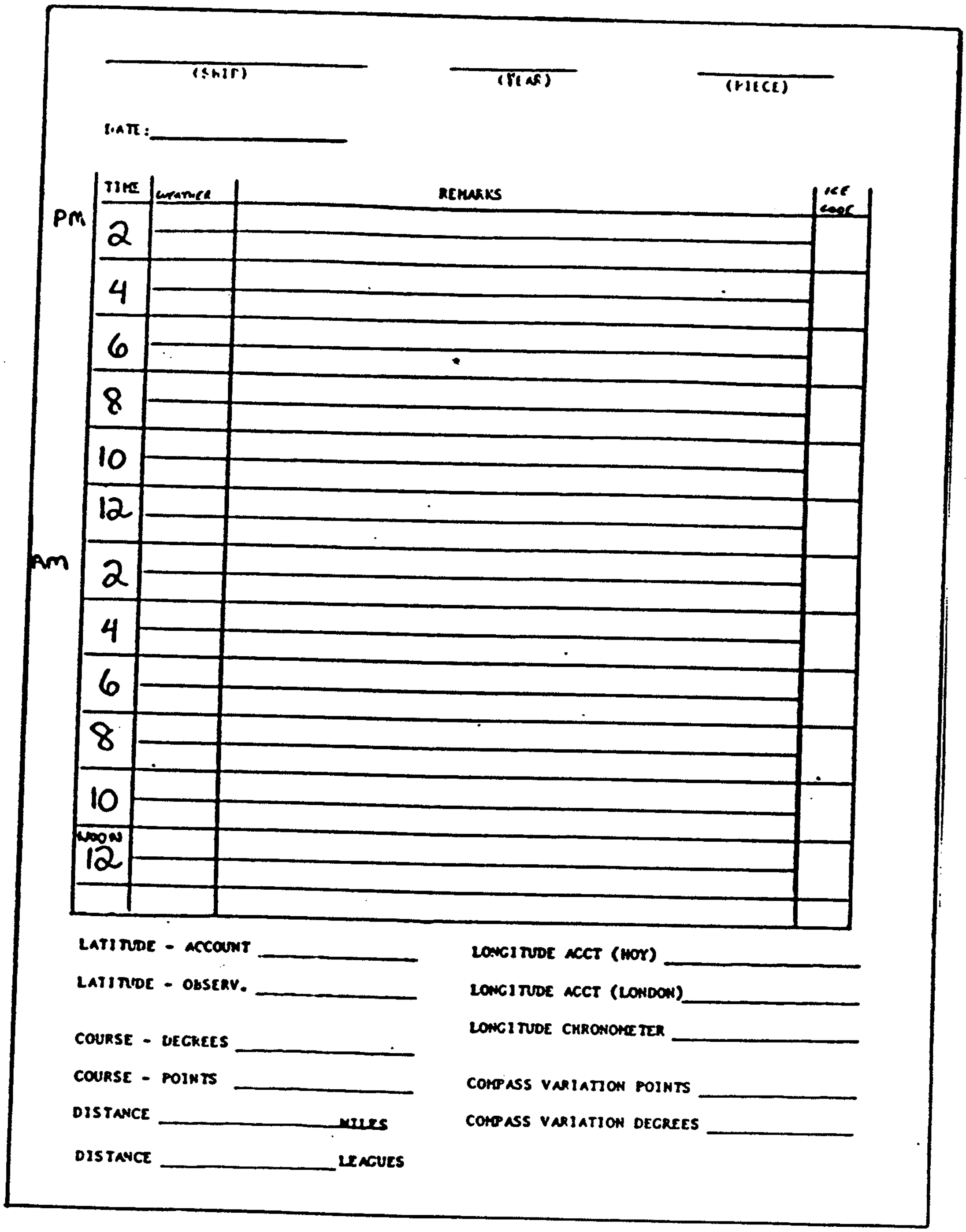
1 The log-keeper has used a symbol to denote per.

* 14 "Lat. [P]. Acct. 61.38 N:" This is latitude by account or dead reckoning. This was calculated from the course and distance run from the previous day's position. Not given in this example is the latitude by observation, in which latitude was determined from celestial observations using a quadrant.

3.2 Transcription of Information from Log-books

The transcription of information from the log-book was made verbatim to ensure that the interpretations of this information would commence after the transcription was complete. Figure 3.2 is a reduction of a blank transcription form, designed to retrieve data for this study. The form is similar in appearance to the log-book page, although it is simplified to accommodate only the data that were determined to be of interest in this study. The form also has an extra column labeled 'ice code' which was used later for the interpretation of the data (discussed in Chapter 5). One of these forms was filled out for each day on which ice or Resolution Island (or any other landmark) was sighted in the study area.

Figure 3.2: Blank Transcription Form



(SHIP) (YEAR) (PIECE)

DATE:

	TIME	WEATHER	REMARKS	ICE CODE
PM	2			
	4			
	6			
	8			
	10			
	12			
AM	2			
	4			
	6			
	8			
	10			
	NOON 12			

LATITUDE - ACCOUNT ______

LATITUDE - OBSERV. ______

COURSE - DEGREES ______

COURSE - POINTS ______

DISTANCE ______ MILES

DISTANCE ______ LEAGUES

LONGITUDE ACCT (HOY) ______

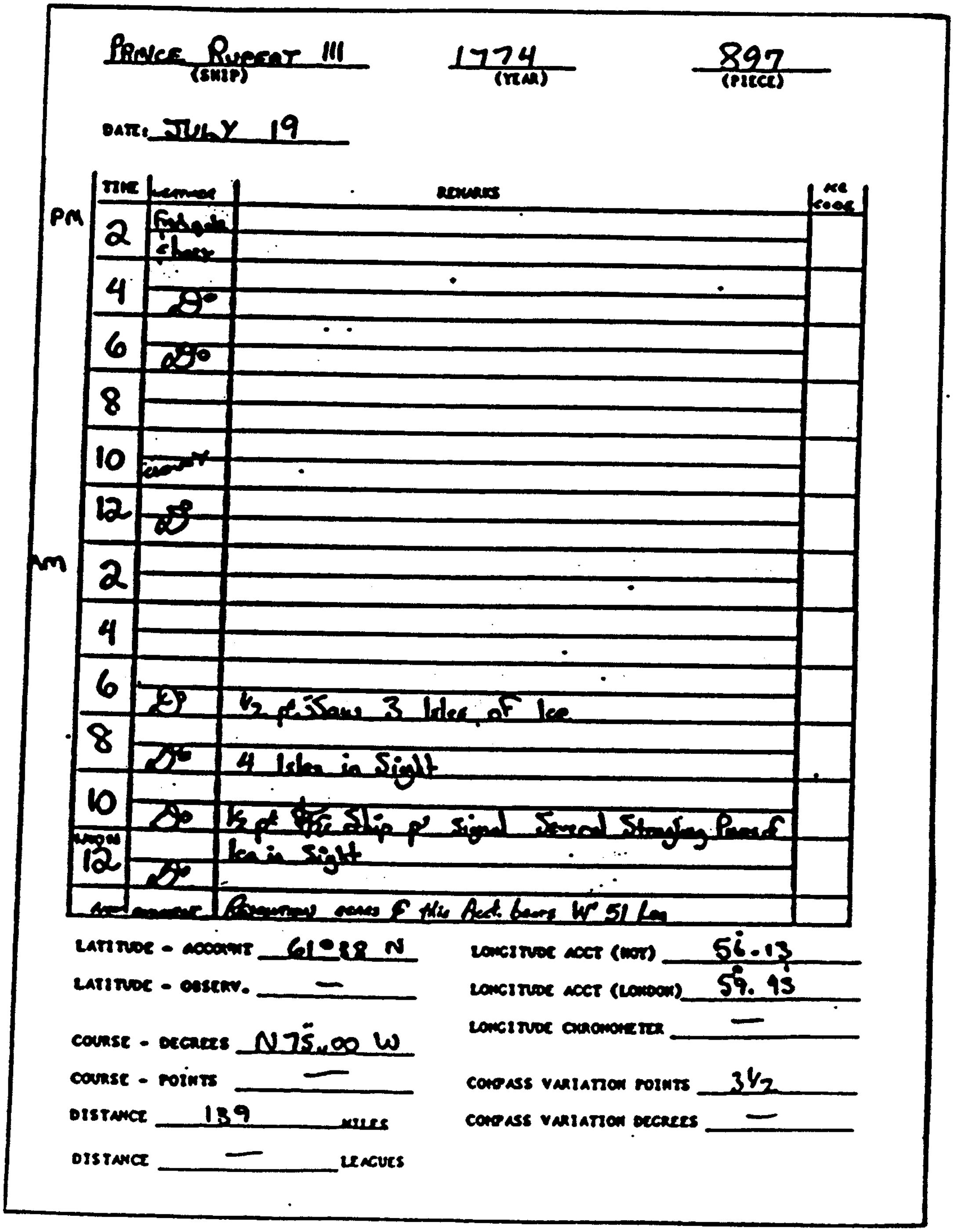
LONGITUDE ACCT (LONDON) ______

LONGITUDE CHRONOMETER ______

COMPASS VARIATION POINTS ______

COMPASS VARIATION DEGREES ______

Figure 3.3: Sample of a Completed Transcription Form



PRINCE RUPERT III (SHIP) 1774 (YEAR) 897 (PIECE)

DATE: JULY 19

	TIME	WEATHER	REMARKS	ICE CODE
PM	2	Fresh gale & hazy		
	4	Do		
	6	Do		
	8			
	10	calm		
	12	Do		
AM	2			
	4			
	6	Do	½ p 5 Saw 3 Isles of Ice	
	8	Do	4 Isles in Sight	
	10	Do	½ p 9 the Ship p Signal Several Straggling Pieces of	
	NOON 12	Do	Ice in Sight	
			Resolution Island ... of this Acct. bears W° 51 Lea	

LATITUDE - ACCOUNT 61°88 N

LONGITUDE ACCT (HOT) 56.13

LATITUDE - OBSERV. —

LONGITUDE ACCT (LONDON) 59.43

LONGITUDE CHRONOMETER —

COURSE - DEGREES N75.00 W

COURSE - POINTS —

COMPASS VARIATION POINTS 3½

DISTANCE 139 MILES

COMPASS VARIATION DEGREES —

DISTANCE — LEAGUES

Figure 3.3 is an example of how the information in the typical log-page, Figure 3.1, was transcribed. All remarks regarding any type of ice condition were transcribed as well as comments on location, such as the sighting of land. Comments on sails, supplies, and the various ways the crew were employed were ignored. The remarks transcribed in Figure 3.3 can be read as follows: The 6:00 am remark is: "1/2 pt. Saw 3 Isles of Ice". This means that at half-past six the crew saw three icebergs. *Isle of Ice* was the most common term for iceberg in the early years. The 8:00 am remark is: "4 Isles in sight". In this example the crew saw four icebergs. Although the phrase did not use the word *ice*, it is obvious that the log-keeper was using an abbreviation, as the ship was nowhere near any land isles. The 10:00 am remark contains the symbol the sailors used to denote tacking (see Appendix 2 for a glossary of sailing manoeuvres).

As well as ice descriptions and information pertaining to location, the name of the ship, the name of the officer keeping the log-book, the HBC Archives piece number, the date the ship left its last port in Britain, and the date the ship actually entered Hudson Strait (defined in Chapter 2.2), were all recorded for each log-book that was transcribed.

Chapter 4: Determining Ship Locations

Before the descriptive ice comments could be properly analyzed, one important question regarding the quality of the data had to be answered. How reliable are locations given in the noon summary at the bottom of the log-pages? The data used in this study can often be located only with the aid of coordinates given by the log-books. As all ships' officers during the eighteenth century had difficulty in knowing their true location, it is important to establish a measure of the accuracy of the HBC log-book coordinates.

4.1 Accuracy in the Determination of Longitude at Sea: 1751 - 1870

"Navigation, in the technical sense of the word, means the art of finding a ship's place at sea, and of directing her course for the purpose of reaching any desired place" (Thomson, 1891, p.1). As this work deals with the location of ice and iceberg sightings taken from ships, the state of the art of navigation in the period 1751 to 1870 deserves careful consideration.

In a ship's log-book the sailors gave a daily reading, at noon, of the ship's latitude and longitude. When at sea, out of the sight of landmarks, the location of the ship was usually determined by "Dead Reckoning", abbreviated D.R. in the log-books. The term "Dead Reckoning" itself is thought to be an abbreviation of "Deduced Reckoning" or "Deduced from Reckoning" which the log-keeper would shorten to "Ded: Reckoning" (Hewson, 1951, p.176). Dead reckoning of position was calculated using direction and distance traveled from a known location. Distance was calculated using the speed of the ship and length of time traveled at that speed, the calculation of which was difficult in the eighteenth and nineteenth centuries. This will be discussed in more detail later in the chapter.

By the middle of the eighteenth century the science and technology to determine latitude accurately at sea were already existent. Thus, daily observations of celestial bodies using a quadrant or sextant could correct errors in latitude calculated by dead reckoning.

Longitude, on the other hand, could not be accurately determined at sea, although as early as 1522 it was known that an accurate timepiece was required for this purpose. Despite the best efforts of the craftsmen of the time, watches and clocks could not keep accurate time because of the motion of the ship and the large temperature ranges encountered at sea. Ships were wrecked and sailors lost their lives with an alarming frequency because of their inability to correctly determine longitude, giving a fatal irony to the term "dead reckoning" (Fillmore and Sandilands, 1983, p.79). In 1713, it was disclosed that a disaster six years earlier with the English fleet in which many lost their lives was caused by an error in longitude (Taylor, 1971, p.253). Public outcry forced parliament on July 11, 1714 to appoint a Board of Longitudes which, in due course, gave "a report explaining different means by which the longitude could be found, and recommending encouragement for the construction of chronometers" (Thomson, 1891, p.36). In response to this report, parliament passed a bill offering a reward of up to £20,000 for the invention of a method to accurately determine longitude at sea.

In 1736, an English clockmaker, John Harrison, had his first chronometer tested on a voyage to Lisbon. In 1762, his fourth chronometer was tested on a voyage to Jamaica. After a delay and more tests he was awarded £10,000 in 1765 (Taylor, 1971, p.261), with the balance to be paid when it was proven that other clockmakers could build as accurate timepieces using Harrison's method. "Subsequently the Board of Longitudes commissioned another clockmaker, Larkum Kendall, to make a facsimile of Harrison's fourth chronometer. This model was carried by Captain

Cook on board the Resolution in 1772, and proved of immense value" (Taylor, 1971, p.262). With the results of Cook's trial and another successful trial by Captain Phipps in 1773, Harrison was given the £10,000 balance in 1775 (Hewson, 1951, p.246).

Even with the success of Harrison's chronometer, the Board of Longitudes continued to offer rewards for improvements up until 1818, when the testing period could be said to be over (Hewson, 1951, p.248). The chronometer was adopted on almost all ships during the nineteenth century. The first HBC ship to use a chronometer was the Prince of Wales I in 1825 (Catchpole and Halpin, 1987) and the HBC ships sampled in this study first used a chronometer on their voyage to Hudson Bay in 1834.

4.2 Testing the Accuracy of Navigation

To test the accuracy of the locational information given in the log-books, three questions regarding the coordinates were considered:

1) How accurately were latitudes determined during the period 1751 - 1870?

2) How accurately were longitudes determined by dead reckoning in the period 1751 to 1833 (hereafter referred to as the *pre-chronometer period*)?

3) Was the accuracy of determining longitude increased significantly with the use of the chronometer in the period 1834 to 1870 (hereafter referred to as the *chronometer period*)?

To answer these questions, a test, named the *landmark sighting test*, was devised to check the accounts by comparing the ship's position given in the log-book with its actual position. The actual position was determined using the sighting of landmarks, if the distance and direction of the landmarks were given. The differences between actual and dead reckoned position were averaged to determine the mean accuracy of the locations given in the log-books. This test was applied to those log-book entries which satisfied all of the following conditions:

1) Sighting of the landmark was within two hours of noon, since the daily records of latitude and longitude were made at noon.

2) The log-book coordinate being tested must be recorded in the noon summary.

3) Both the bearing (direction) and distance of the landmark from the ship were given, or alternatively, the bearings of two landmarks were given so that the position could be mapped by triangulation.

4) Because of the high latitude, the compass variation must be recorded in the log-book to permit a correction for the difference between true north and magnetic north. This is important as bearings were recorded using the ship's compass.

5) Also it is important for the geographical position of the landmark to be known. While several landmarks on Resolution Island were referred to by the sailors in the logs (such as Cape Resolution, North East Bluff of Resolution, East Bluff of Resolution, West Bluff, Southern Point, and Hatton's Headland), it is difficult to locate some of these landmarks precisely. For example, there are several bluffs on the east coast of Resolution Island and it is unclear which of these was referred to as East Bluff or NE Bluff. This means that the several references to the East Bluff or NE Bluff cannot be used to check latitude. However, they can be used to check longitude since the bluffs are closely aligned from north to south. A less ambiguous landmark, such as Cape Resolution, must be used to determine latitude. Even the sighting of Cape Resolution must be used with care. An 1897 navigational chart placed Cape Resolution in the location of Cape

Warwick. However, by using triangulation through the use of multiple landmark sightings it was confirmed that the HBC sailors considered Cape Resolution to be the cape at the southern point of Resolution Island, and not at the location of present day Cape Warwick.

6) Lastly, the landmark sighting must be the first such sighting after the trans-Atlantic voyage to ensure that the log-keeper had not yet had an opportunity to correct his accounts by observation. At this point, the ship had been out of the sight of land for about 31 days on average and the greatest errors in dead reckoning had probably accumulated.

Sightings of landmarks were used to locate the actual position of each ship and this position was compared to the dead reckoned location of the ship given in the log-book. For example, on July 31, 1809 the log-book of the Prince of Wales I stated: "at noon saw Cape Resolution bearing NNE 7 L". The compass variation was recorded in the log-book as four points west. As a 32 point compass was in use, four points represents a compass variation of 45°. Figure 4.1 illustrates this compass variation, and shows how the location of the ship is mapped using landmark sighting. Once compass variation is accounted for, the ship can be located at 61°02 N and 64°36 W at noon on July 31, 1809. Figure 4.2 demonstrates the difference between the true location based on landmark sighting, and the location given in the accounts of the log-book.

As expected from the historical development of navigation, the HBC officers were able to determine latitudes with greater accuracy than longitudes. Table 4.1 gives a summary of the accuracy tests. On the average, latitudes were accurate within 8 minutes (or nautical miles) of their true value. The negative sign given with latitude in the table indicates that the error was a consistent error in one direction. The log-book accounts consistently placed the ship north of its actual position. This can be accounted for by the southerly current of the Davis Strait. In the 83 years before the adoption of the chronometer in 1834, the longitude by account or dead reckoning was good for the technology available at the time. An average error of less than 30 nautical miles on a trip of well over 1700 miles between landmarks is less than 2%, which is quite remarkable, considering the method which was employed to determine longitude. However, it is far less accurate (significant to 99.9%) than longitude by chronometer, which was able to place the ships within 5 miles, on average, of their actual positions. In 1782, one of the years before the adoption of the chronometer, the longitude by account

Table 4.1: Summary of the Landmark Sighting Test Differences between Log-book and True location.

	Pre-Chronometer Longitude	Chronometer Longitude	Latitude
Number of Observations	24	5	10
Mean Difference*	29.2	5.0	-8.0**
Maximum Difference*	67.7	10.6	14.0

* values are given in nautical miles
** negative sign indicates a consistent error to the south

was particularly inaccurate. On August 1, in his log-book, Captain Jonathon Fowler entered this comment:

> [A]bout 1/4 before noon we fell in with land which we take to be Resolution.... Nearest land NbE about 2 miles... - Made the signal and spoke the Captains of our other ships - we all believed the land seen to be Resolution, but the weather being thick, and not being near the land by any of our accounts; was in some little doubts.
>
> Nb this is the worst account I ever kept since I can remember.
>
> *(HBCA, PAM, King George III log-book, August 1, 1782, C.1/386.)*

Figure 4.1: Mapping the True Location of the Prince of Wales using Landmark Sighting, July 31, 1809.

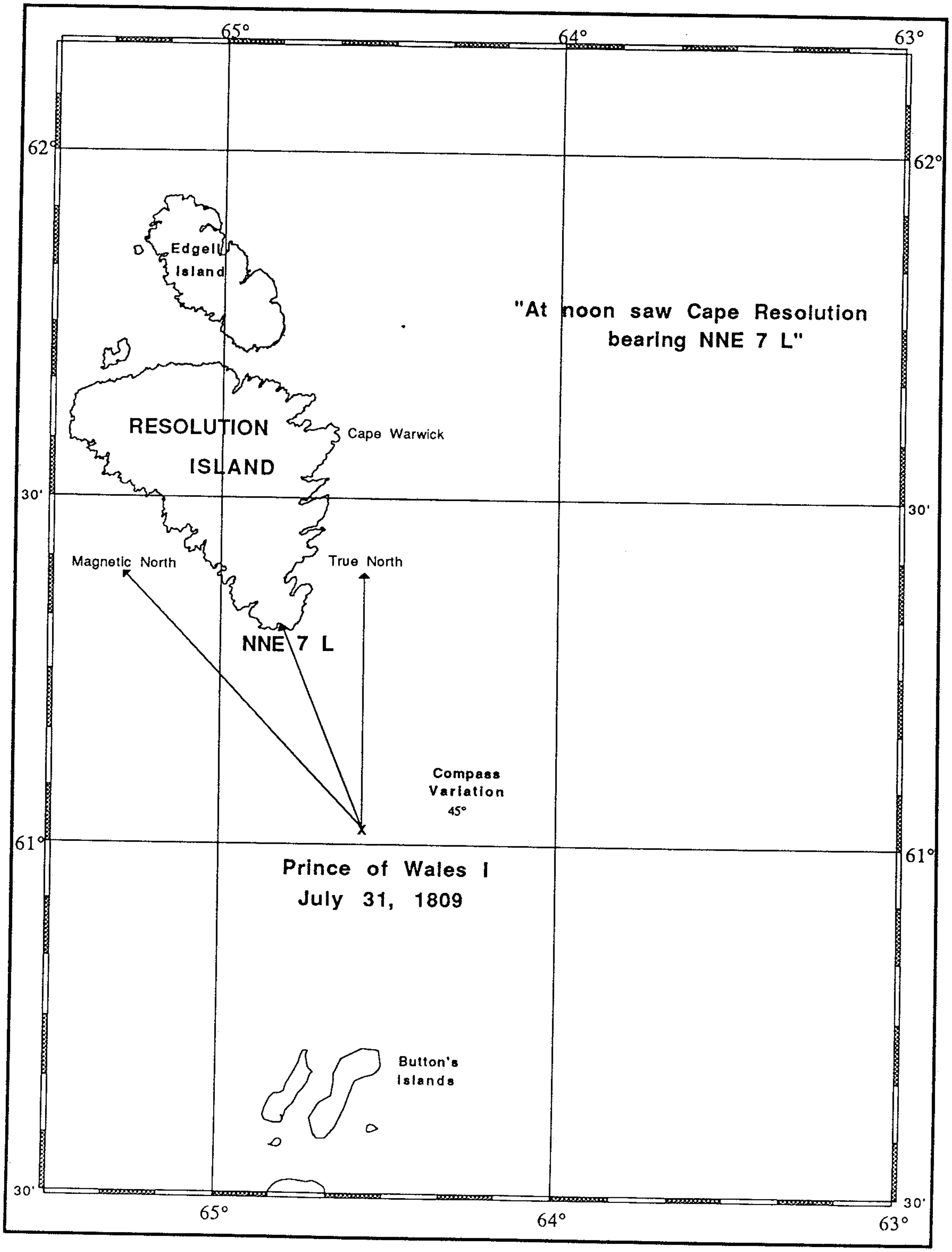
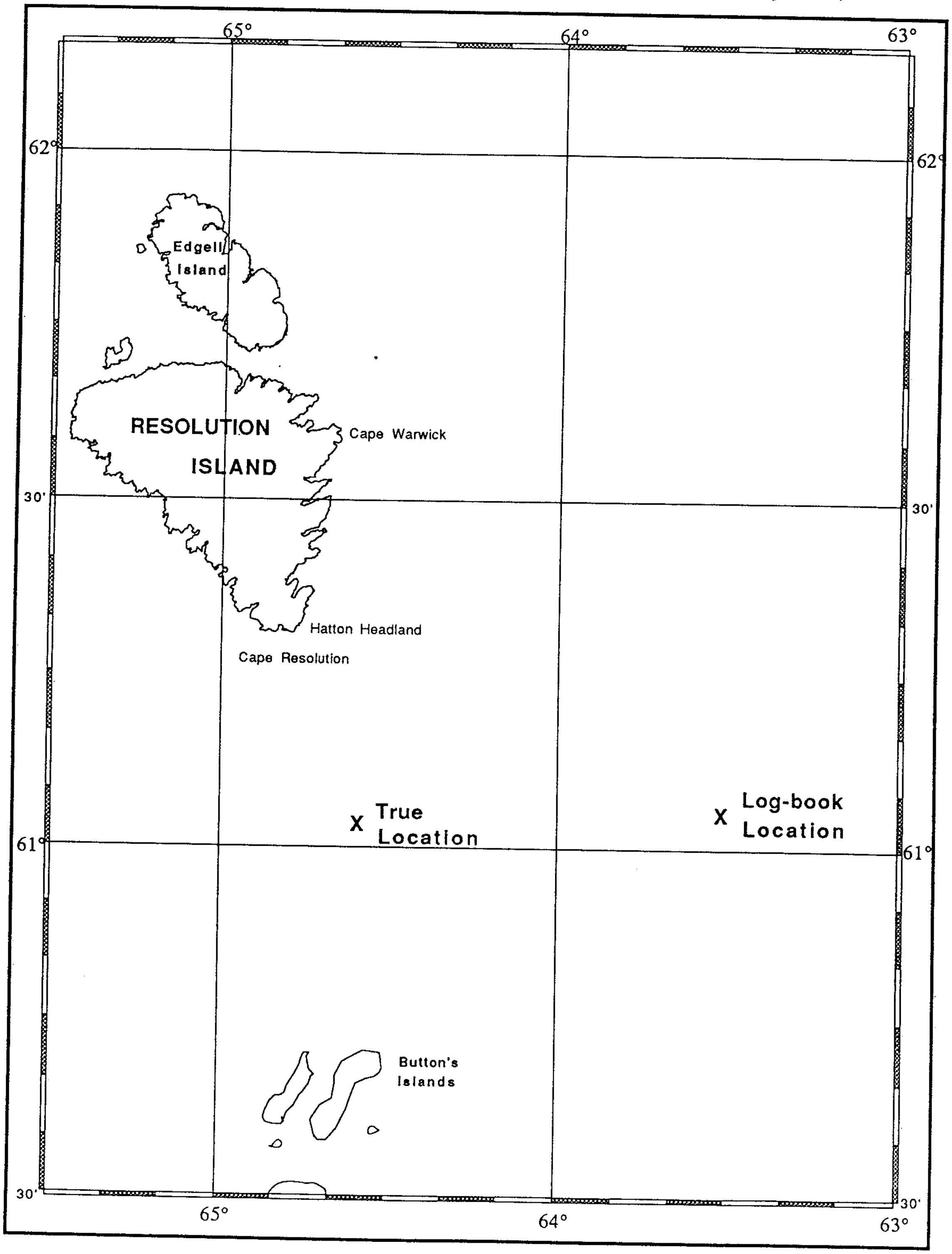


Figure 4.2: Comparison of True Location and Location by Account of the Prince of Wales, July 31, 1809.



In his log-book accounts, Captain Fowler had placed the ship at longitude 53°50 W of Hoy. This was about 7°30 east of the ship's actual position, an error of about 225 miles. This is by far the worst account of all log-books sampled in this study. It is fortunate that there were no ice sightings during the Atlantic crossing in 1782, since it would have been very difficult to locate these with any degree of accuracy.

Independently, Catchpole and Halpin (1987) devised a different method for determining the navigational accuracy of the same HBC ships. Their test, named the *close consort test*, compares the coordinates given in the accounts of the log-books of ships sailing close together. Catchpole and Halpin tested longitude in the pre-chronometer period, latitude by account (dead reckoning), and latitude by observation (using a quadrant or sextant). Their use of a log-book comparison method yielded similar accuracy findings to the landmark sighting test. The results of both tests are given in Table 4.2. Their results of 4 and 9 miles for the accuracy of latitude by observation and account respectively agree well with the landmark sighting test findings of 8 miles. The close consort test found longitude to be in error by 25 miles on average, and this again is close to the 29.2 mile average error detected in this study.

Figure 4.3: Marine Grid Demonstrating Uncertainty of Position Obtained by the Landmark Sighting Test.

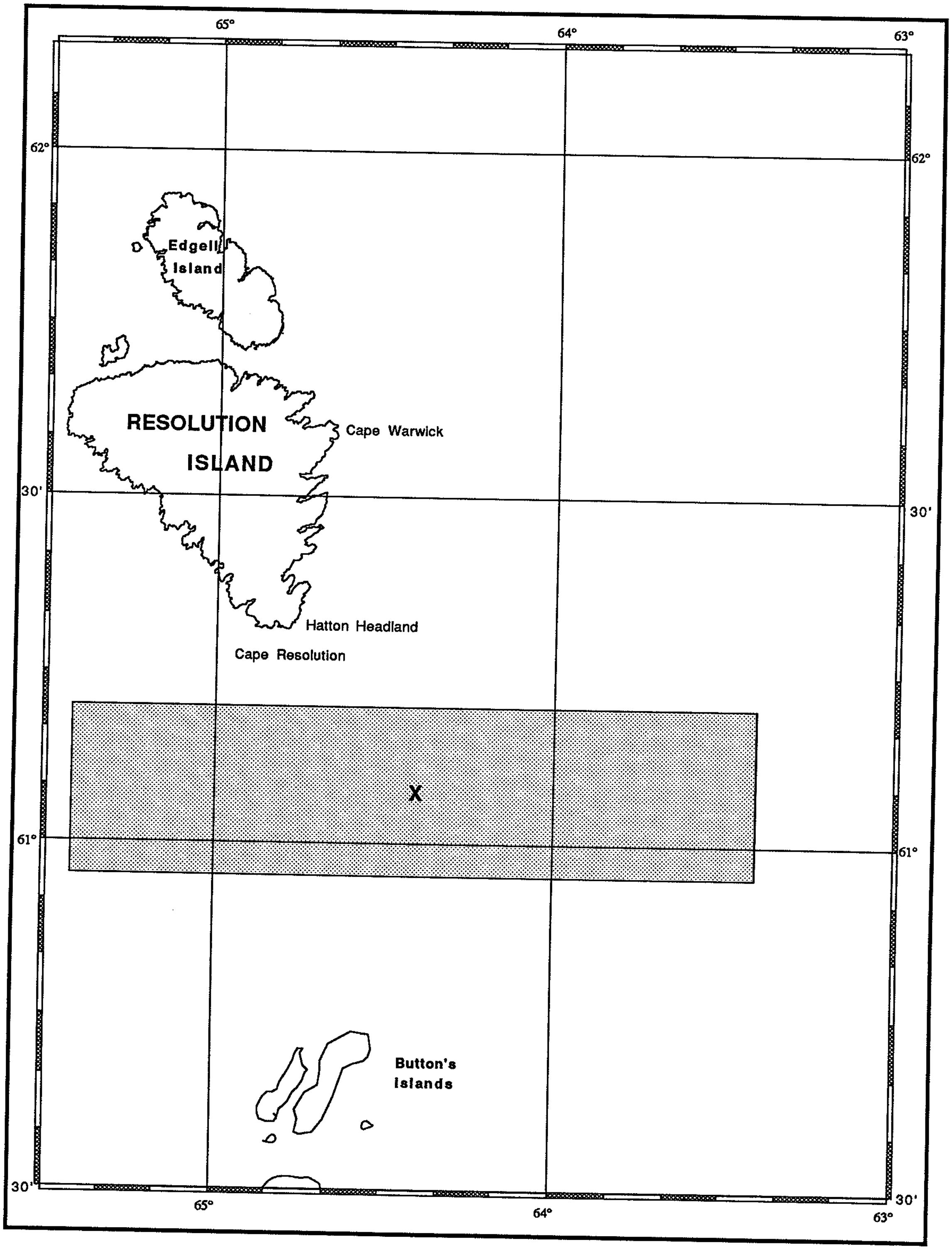


Table 4.2: Comparison of the Results of the Close Consort Test and the Landmark Sighting Test.

	Mean error in Nautical Miles	
	Close Consort Test	*Landmark Sighting Test*
Longitude (by account)	25	29
Latitude		
Observation	4	
Account	9	8

4.3 Locating Ice Descriptions in Marine Sectors: A Correction Factor to Improve Accuracy

A major advantage of the landmark sighting test is that it gives the actual accuracy of the log-book accounts. A problem that arises when trying to use the results of the close consort test employed by Catchpole and Halpin is that it only gives the discrepancies between two different accounts without giving the actual error between real and dead reckoned positions. As can be seen from Table 4.1 the error can be as much as 140' or 2°20 longitude, an error of nearly 68 miles. Unlike the error in latitude, there is no consistent direction to the longitudinal error, so that the mean error of 1° longitude could be either east or west. The position of the ships cannot be located precisely because of the uncertainty in the log-book coordinates. However, they can be located within a rectangular area, or grid box, whose size is determined by the accuracy of the accounts. Figure 4.3 shows how large the dimensions of a grid box would have to be using only the mean error. This grid box is two degrees longitude (58 nautical miles) by 16 minutes (or nautical miles) latitude and by definition only about half of the ships could be located with reasonable certainty within this grid box. With such a large range in accuracy and with a mean error of over 1° longitude and a standard deviation of over 44', the use of log-book coordinates to locate a ship within this large grid cannot be justified. This uncertainty in locating the ships and, by implication, uncertainty in locating the ice encountered by the ships requires either the use of a coarse grid network or else a method of increasing the accuracy of the log-book coordinates. A coarse grid network would significantly diminish the quality of the ice information that is available. However, since the exact error of the log-book coordinates (within a couple of miles) is known when the ship is within sight of Resolution Island, a correction factor can be applied to improve the accuracy of the log-book accounts. By increasing the accuracy of the accounts the uncertainty in locating the ships is decreased and the ships can be located within a finer grid network.

For almost half of all ice sightings, the longitude entered in the log-books was not important as the ship was also within sight of Resolution Island and longitude could be determined precisely by observation. However, in the other half of the cases the ship had not yet sighted land and her officers had not yet been able to correct their accounts. Often a log-book showed a sizeable error between the longitude by account and the actual longitude, which was eventually determined when the ship was within sight of Resolution Island. The location of the Prince of Wales I in 1809 is an example of this (Figure 4.2).

The method used to correct the longitude by account was based on the assumption that the error at Resolution Island had gradually accumulated during the voyage. When this final error is divided by the number of days spent on the Atlantic crossing, the result is an estimate of the mean daily error. Using 1809 for example, the longitude entered in the accounts of the Prince of Wales I is 63°32 although their true longitude was mapped as 64°36 (Figure 4.2). This gives an error of 1°04 which is nearly 31 nautical miles. With the assumption that this error was cumulative over the 33 days between port and first land sighting by the crew of the Prince of Wales I, a correction factor of 1.94' per day is obtained using equation 1. This equation calculates the correction factor, CF, by dividing the difference between the actual and dead reckoned longitudes, DIFF, by the number of days at sea (from port to landmark sighting), D.

$$\text{Diff} \div \text{D} = \text{CF} \qquad (1)$$

$$\text{Long Acct} + (\text{CF} \times \text{d}) = \text{Corrected Long} \qquad (2)$$

The correction factor, CF, is used in equation 2 to give the corrected longitude. Multiplication of the CF by the number of days out of port, d (which on July 30, 1809 would be 32 days; on July 31, 1809 it would be 33 days), and adding this product to the longitude by account given in the log-book (61°14 on July 30; 63°32 on July 31), gives the corrected longitude for that day (62°16 on July 30; 64°36 on July 31).

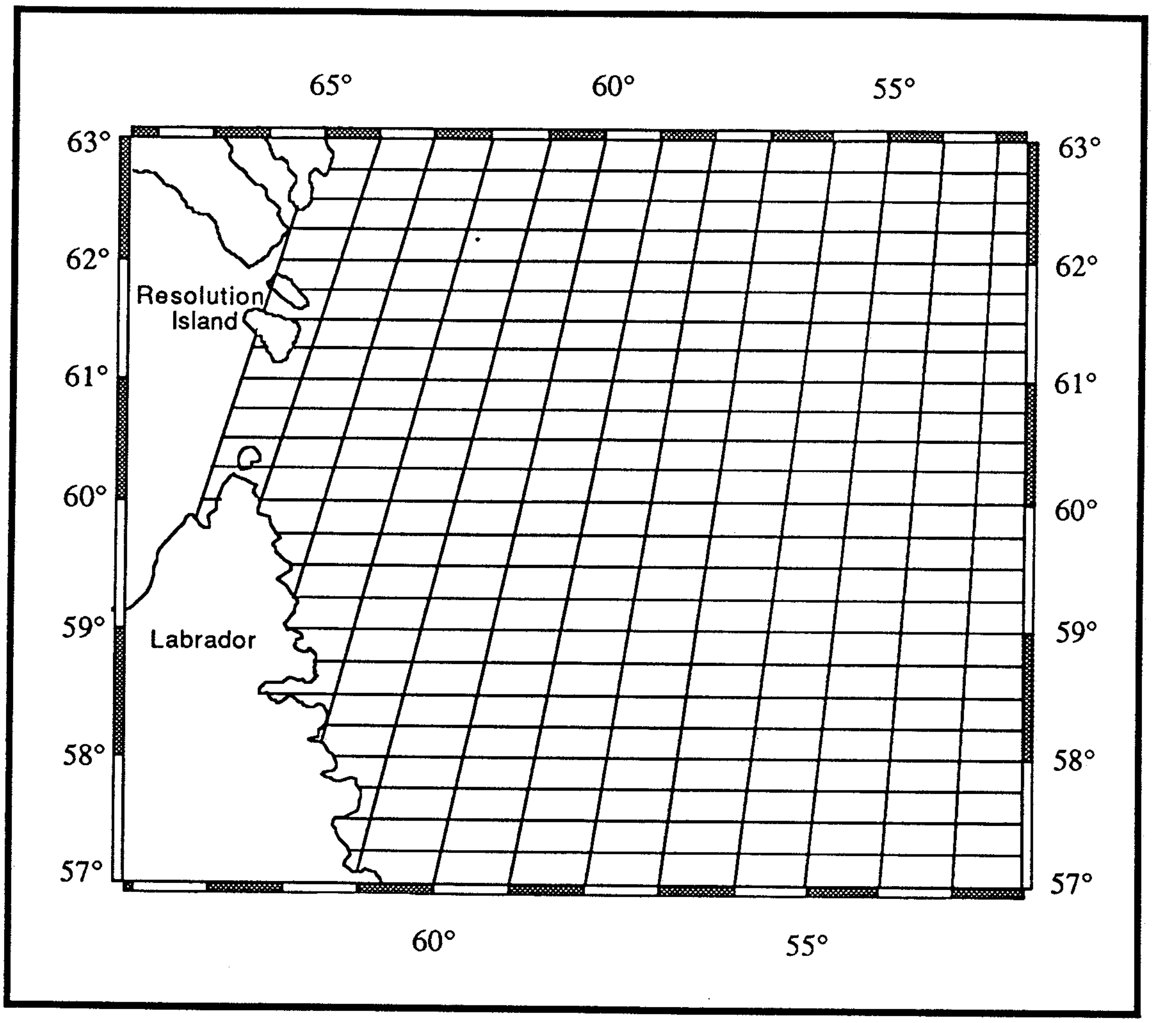
In some cases it was apparent that the errors had not accumulated over a period of time but were singular discrepancies. An example of this is found in Captain Henry Hanwell's log-book kept during his 1810 voyage on board the Prince of Wales I. On July 14, 1810 Captain Hanwell entered the longitude by account as 55°08 from Lewis (about 61°30 from London). On July 15 he recorded the longitude as 61°20 from

Lewis. For the Prince of Wales I to be at both of those locations it would have had to sail a distance of over 180 miles in one day. In his July 15 noon summary, however, Captain Hanwell had determined that the ship had traveled a distance of only 29 miles in the previous 24 hours. By checking the speed of the ship for those 24 hours it became apparent that the figure of 29 miles is the correct one, as the ship was sailing at a speed of one knot most of the time. It appears that Captain Hanwell simply made the mistake of writing down the value for latitude by observation (which was 61°20) in the place for longitude. To confirm this, the log-books of the first and second mates were consulted. The first mate, Jon Davison, had entered the longitude for July 15 as 55°54 from Lewis. This together with a similar reading in the second mate's log-book shows that Henry Hanwell's July 15 account was in error.

In those years when the sighting of Resolution Island was not within two hours of noon an estimate of the accuracy of navigation could, nevertheless, be made in most cases. For example, in 1757, the Prince Rupert I log-book on July 27 stated at 4:00 am: "Et Bluff of Resolution WNW 4 Leagues". This would place her at about 64°20 W. Twelve hours later a second entry at 4:00 pm places the ship at about 65°00 W. Yet at noon, in between these two landmark sightings, her longitude by account was 61°40 W, despite a continuous westward course. There is an obvious error of at least 2°40 and at most 3°20. The actual longitude can be estimated as 64°47 W, producing a difference between actual and dead reckoned longitude of 3°07. The Prince Rupert I was at sea for 38 days between her departure from the Orkney Islands and her first sighting of Resolution Island. If the difference is divided by the number of days at sea (equation 1), a correction factor of 4.92 minutes per day is produced. This correction factor can now be used in equation 2 to calculate corrected longitudes on previous days.

Even when the landmark sighting is available and the correction factor is applied, the locations of the ships cannot be fixed precisely. However, by employing the correction factor the location of the ship can be made far more precisely than the uncertainty displayed in Figure 4.3. The location can be determined accurately when the ship was within sight of Resolution Island. Even though accuracy decreased as the ship's route was traced back from Resolution Island, the ship could easily be located within an area of 1° longitude by 15' latitude. The entire study area was divided into grid sections of 1° longitude by 15' latitude (Figure 4.4). All ice sightings were corrected (when necessary) and located within these marine sectors.

Figure 4.4: Network of Marine Sectors in the Labrador Sea



Chapter 5: Derivation of the Ice Severity Index from the Ice Descriptions

The preceding chapter provided the conceptual basis for the establishment of the network of marine sectors and identified the procedures used to determine the ship locations within this network. By these means, the noon locations of each daily log-book entry can now be obtained. The next stage in the analysis involves the interpretation of the ice descriptions written at these noon locations. The purpose of this interpretation is to derive numerical measures of the ice conditions from the qualitative descriptive information. Originating as they do from a large collection of log-books written by many individuals over a long period of time, the ice descriptions are highly subjective. Therefore, the need arises to develop an objective method for the interpretation of these descriptions. The level of objectivity in this context is determined by the degree to which different people will obtain the same results when they apply the method to the same sources. In this chapter the general principles of content analysis are applied in the development of this method of analysis.

The first stage in the content analysis involved the identification of the individual word roots and phrases which appeared, in a multitude of different semantic forms, within the entire body of ice descriptions. These word roots and phrases were then classified into categories. These categories determine the types of ice information which might be derived from the log-books. In the final stage the categories are ranked to provide a scale of ice severity.

5.1 The Word Roots and Phrases

The content analysis for this research involved the transcription of nearly 2500 comments in the 117 log-books sampled. This number swelled to approximately 3000 when other log-books from the same year were included. About 1000 of the 2500 comments were not ice related and dealt mainly with locational information. There were 1441 pack ice and iceberg comments in the 117 years, which amounts to about 12 comments per year. There were only three years in which neither pack ice nor icebergs were seen. Of the 1441 pack ice and iceberg descriptions that were transcribed, 546 dealt with icebergs and were immediately set aside for separate study (Chapter 8). There were no pack ice observations in 23 of the 117 annual voyages, leaving 94 years with pack ice observations. There were an average of 9.5 pack ice comments per year in those 94 years. The year 1816 had by far the largest number of ice descriptions with a total of 117. The next highest was 68 descriptions in 1832. The 895 descriptions of pack ice were analyzed using content analysis to obtain five levels of summer sea ice severity for the Labrador Sea.

As Catchpole and Halpin (1987) found in their study of ice descriptions, instead of the high variability one might expect in the words used to describe the sea ice conditions, there was much uniformity over all the years and from log-keeper to log-keeper. It was found that a content analysis using only 45 word roots and phrases was capable of classifying all 895 of the pack ice descriptions in this study. The 45 word roots are given by category in Figure 5.1. This content analysis was developed from an earlier content analysis derived by Catchpole and Halpin (1987). Similarities remain between these analyses but they do differ in some important respects. One similarity is that both analyses recognize two main types of log-book entry. The first was strictly descriptive of the appearance of the ice, and the second described the type of encounter with ice or the sailing manoeuvre while passing, traversing or avoiding ice.

The comments that described the ice were usually terse adjectives and verbs. The ice was often described as *loose*,

Figure 5.1: Ice Severity Codes Derived from the Classification of Word Roots and Phrases

		Ice Severity Codes				
		0	1	2	3	4
		Ice Absent	Very Open Pack Ice	Moderate Pack Ice	Severe Pack Ice	Ice Closed
Word Roots and Phrases	Ice Description	clear sea open water no ice	piece (small pieces) stream skim loose shatter'd stragling open ice	point body field (fast) ledge heavy fast (large) close very thick much		
	Ice Encounter or Sailing Manoeuvre		saw (in sight) [often implied] fell (in, with, to) sailing passed traversing enter'd running [+ other vague references]	wore tack'd alter'd course steer'd veer'd working rounded	drove within forcing weather'd drifting past Hall'd up Brought too bore away standing on & off	beset embayed fast in grappled (grappling) [any damage to ship]

stragling, or *heavy*. From simple descriptions of ice, such as these, it is impossible to determine the percentage of sea covered in ice, the age of the ice, or many of the other aspects of pack ice which are routinely observed today. Nevertheless, they are capable of yielding a simple nonparametric index of ice severity. Additional information was provided by the word roots which described the nature of ice encounters and sailing manoeuvres. The ice encounters ranged from the passive where the crews could *see* ice or the ships *sailed within* the ice, to the more active, where the crews were forced to take evasive action such as *tack'd*, *wore*, or *alter'd course*. The most severe ice conditions were revealed when the ship was *beset by*, *fast in* or *embayed in* ice, and when the ship was damaged by ice. It was common for a log-book description to include both types of comment. For example the comment: *Tack'd from a large body of Ice* contains both types of information since the ice is described as a large body and the sailing manoeuvre is identified as tacking.

5.2 Categories of Word Roots and Phrases

The ice categories presented here and in Catchpole and Halpin (1987) are very similar, but not identical. One of the most obvious differences is that icebergs are part of the content analysis used by Catchpole and Halpin, but they are set aside for separate study here. In fact icebergs do not occur in Hudson Bay and thus this category was not used by Catchpole and Halpin. Catchpole and Halpin (1987) assigned four ice severity codes from 0 to 3, with 0 being a condition of no ice and 3 being the most severe ice condition. The content analysis used in this research distinguishes five codes ranging from 0 to 4, again with 0 representing a condition of no ice and 4 being the most severe ice condition. The categories designated 0 are identical in both studies. The most severe codes (3 in Catchpole and Halpin, and 4 in this study) also indicate similar ice conditions. The two studies differ insofar as Catchpole and Halpin recognize one intermediate code while two are identified here.

The following is a detailed description of each of the five ice categories used in this analysis:

Code 0 was applied to log-book entries which specifically stated that there was no sea ice present. For example the comments "no ice in sight" or "in a clear sea" would each be given a code of 0. This category was applied to only 16 log-book comments (1.8% of total).

Code 1 represents the least severe ice condition where ice was observed, and this was termed *very open pack ice*. This code was assigned when the ship's progress was not significantly delayed by the ice. Code 1 also included miscellaneous and vague references to ice that could not be justifiably coded as more severe. This code was applied to over 35% of the comments.

Code 2 was applied to ice conditions which necessitated avoiding action by the ship without the ship being forced to come into contact with the ice. This action often involved tacking but it allowed the ship to make good progress along the original course. Code 2 was applied most frequently (over 40%) and this high percentage can probably be attributed to the large size of the Labrador Sea. In its large expanse the crews of the HBC ships were usually able to avoid large, congested ice covered regions and still make progress.

Code 3 was applied when the HBC ships came into physical contact with the ice and were able to proceed by forcing a passage. Code 3 was also applied if the crews were forced to *haul to* or stop sailing to avoid contact with ice. Code 3 was applied to only 8.7% of the 'ice present' categories and only applied on 36 days during the period 1751 to 1870 which, again, is probably a reflection of the very large area the ships were sailing in. Room to manoeuvre was a luxury that the HBC crews often did not have later in the narrow confines of the Hudson Strait.

Code 4 represents the most severe ice condition, in which the ship's passage was completely blocked, and the ship was in contact with ice. For Code 4 to be applied, the ship was *beset by* or *embayed* in ice, or else it had *grappled* to a piece of ice. A rank of 4 was applied to 13.2% of all the comments classified. This most severe of categories was also applied to any log-book comments describing damage to a ship by ice. Ice descriptions were only severe enough to indicate a Code 4 rating in 18 of the 117 years. In total, Code 4 was applied on 67 days during the entire period 1751 to 1870.

5.3 Coding: The Ice Severity Index

An effective annual ice severity index must satisfy three conditions. Firstly, it should include some measure of the severity of the sea ice encountered. Secondly, there should be a measure of the time of year at which the ice was encountered. This was important since ships sailed at different times in the summer ice dispersal period and this affects the expected ice conditions. Lastly, the ice index should have some basis for calibration against modern conditions.

The measure of ice severity was obtained by coding all word roots and phrases. When an ice description involved several word roots, the code assigned was the most severe of the alternatives. Thus all ice comments were given a single code using the content analysis in Figure 5.1 (an annual breakdown of ice severity codes, by comment, is given in Appendix 3). Some examples taken from the log-book of the Prince of Wales I in 1816 were coded as follows:

Code	Ice Comment
2	Tack'd from a body of Ice.
1	saw several pieces of Ice.
3	forcing through heavy Ice.
4	Ice very close. Grapled to a piece of Ice with the Emerald.
0	In a clear sea.
1	Among stragling Ice.

For the determination of an ice code for the entire year, the use of the total number of ice comments or codes was not appropriate. This total was highly dependent on the diligence of the log-keeper and the changeability of ice conditions, rather than ice severity. For example, the log-book of the Prince of Wales I, kept on July 25, 1816 had only one ice comment for the entire day, but this is indicative of severe ice persisting all day: "All these past 24 hours ... the Ice very close and heavy, continue at grapple with Emerald" (HBCA, PAM, Prince of Wales I log-book, July 25, 1816, C.1/785).

Following the coding of the individual ice descriptions, the next step was to assign an ice severity code, **s**, to each day. The daily code was determined by the most severe ice condition encountered that day. The most severe condition was selected to represent each day as this was the ice condition that would have commanded the most attention from the crew in their efforts to avoid the ice (an annual breakdown of **s** is given for codes 1 to 4 in Appendix 3). While in the Labrador Sea the presence of ice could not be inferred for a particular day unless it was noted in the log-book. Days in which the presence of ice was not entered in the log-book were assigned a daily value of 0, i.e., they were assumed not to have ice unless the presence of ice was specifically mentioned.

The next stage involved building in a basis for determining the impact that the time of sailing in the summer period of ice dispersal had on the severity of the ice conditions encountered. The method adopted was similar to the one employed by Catchpole and Halpin (1987), in which the date of each ice encounter was compared with observed ice dispersal dates in the period of the modern record. This approach has an element of subjectivity since a decision must be made regarding the stage in the dispersal process to be chosen as the yardstick for comparison with historic conditions.

From the analysis of modern ice clearing in Chapter 2.3, the late pattern of retreat (1973 example, Figure 2.11) shows a small ice free area immediately south of Resolution Island by July 16, although much of the eastern approach to Resolution Island is ice covered until August 20. These late ice clearing dates make it difficult to compare modern to historic conditions as over 95% of the HBC voyages had entered Hudson Strait by August 13, and thus any ice encountered by then could be expected during a severe year. In an average year, defined by the median ice edge (Figure 2.9), the entrance to Hudson Strait is clear of ice shortly after July 23. However, Figure 2.7 shows that in nearly 30% of the years the ships had already entered Hudson Strait by July 23. This indicates that this date is not a suitable yardstick against which to measure the time of year when the ice was encountered in the Labrador Sea, although the date of the median ice limit was adopted by Catchpole and Halpin for this purpose in Hudson Bay.

The dates of ice dispersal in 1965, the year selected to illustrate the early pattern of ice retreat (Figure 2.10) were chosen as the standard against which historical dates of ice encounters were compared. In this year, the last ice at the entrance to Hudson Strait was on June 25. In all years except one, the HBC ships entered the Strait after June 25. This indicates that the ice conditions in 1965 may provide a suitable yardstick against which to measure the seasonal lateness of the ice encountered by the ships.

With knowledge of: the marine sector in which each each ice sighting occurred; the date of last ice in that marine sector in 1965 (Figure 2.10); and the date of each ice sighting; the value of the lateness index, **d**, was then derived. This lateness index was similar to that developed by Catchpole and Halpin (1987), with the main difference being the methods of measuring seasonal lateness as outlined above. The lateness index is calculated from the difference in days between the date when ice was sighted by the HBC crew and the date of last ice in the corresponding marine sector in 1965. This difference in days was assigned a **d** value using Table 5.1. Any ice sighting made on or before the date of last ice for the corresponding 1965 marine sector was considered as ice that would be present there during the mildest years today. This ice was not late and received a **d** of zero.

Figure 5.2: An Example of the Derivation of the Daily Ice Severity Index

Prince of Wales I July 27, 1836

Log-book Comment:

at 5 am within hail of the Rupert both being embayed in among the ice - Commadore being first clear, bore away

Latitude by Account: 61°21
Longitude by Chronometer: 64°14

Calculation of s and d

s = 4, From Content Analysis, Figure 5.1

d = 4, From Figure 5.3 and Table 5.1

date ice encountered in 1836	=	July 27
date of open water in 1965 for corresponding sector	=	June 25
Difference (Lateness of Ice)	=	32 Days

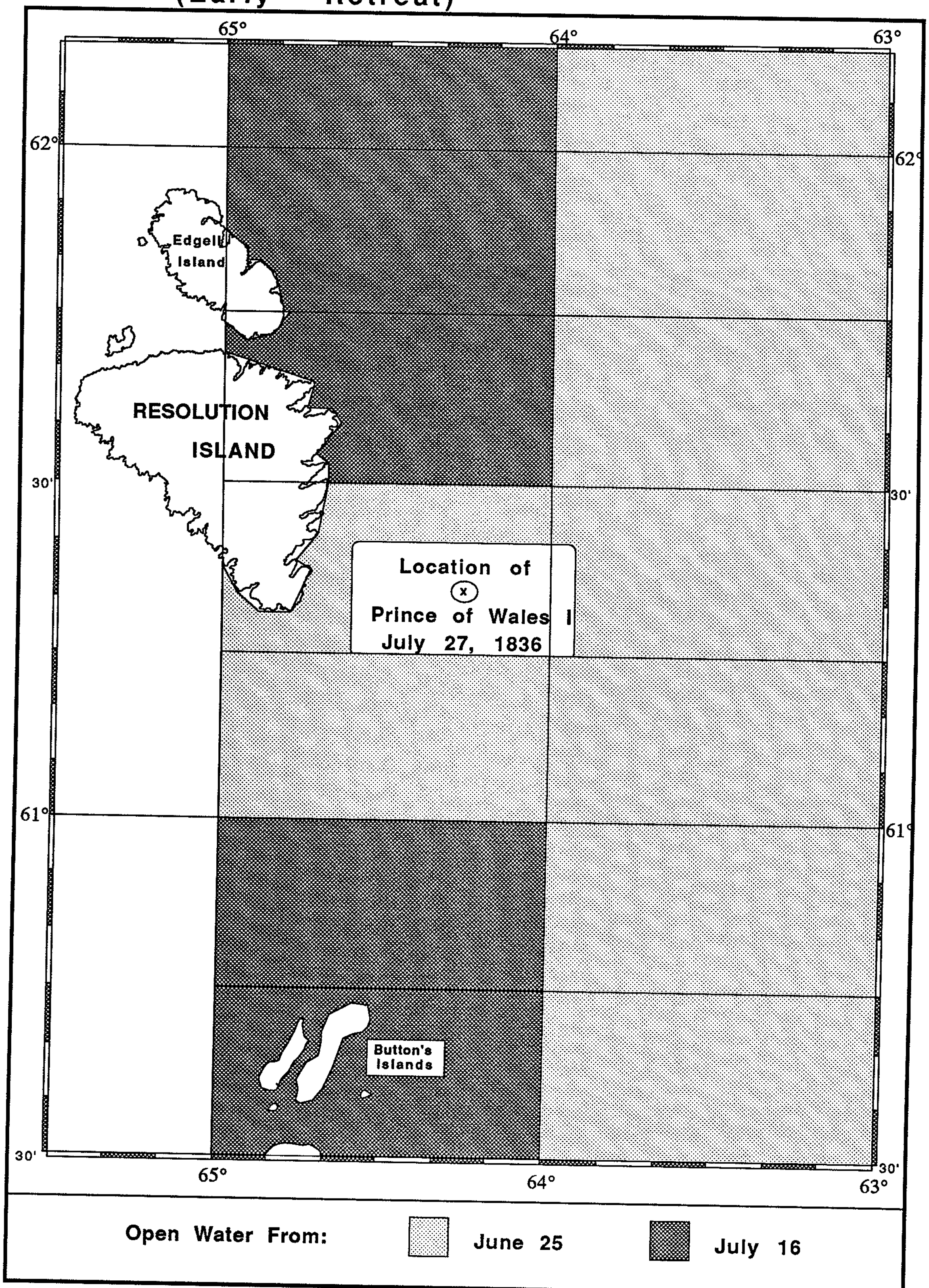
32 days, d=4 (from Table 5.1)

Daily Ice Index = d x s
= 4x4

Daily Ice Index = 16 (For July 27, 1836)

(HBCA, PAM, Prince of Wales I log-book, July 27, 1836, C.1/380)

Figure 5.3: Dates of Last Ice for 1965 Season (Early Retreat)



(from Figure 2.10)

Table 5.1: Lateness Index, d

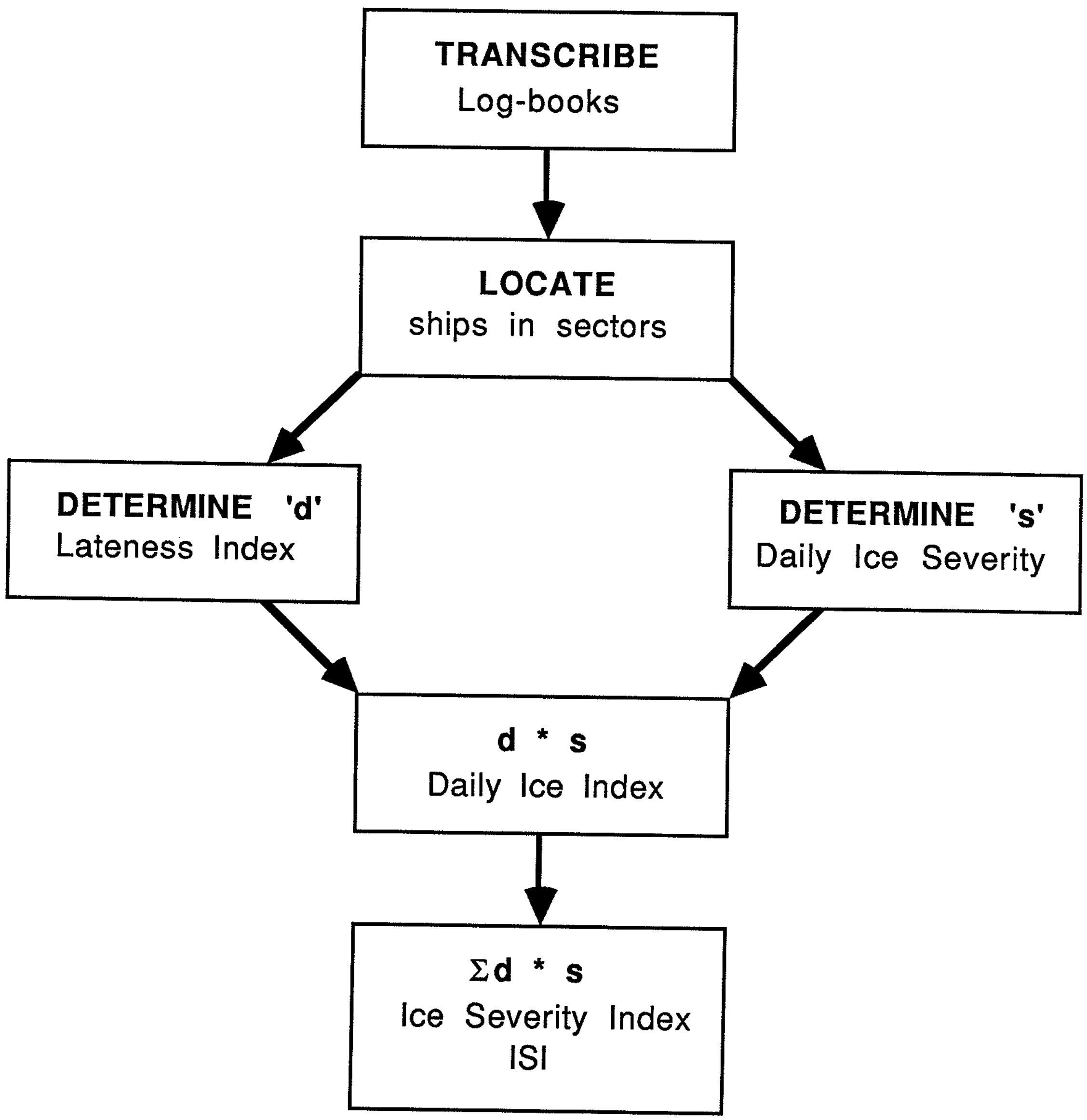
Based on the interval in days between the date of the ice sighting and the first date of open water in the corresponding sector in 1965.

Interval in days	numerical value of d
1 - 10	1
11 - 20	2
21 - 30	3
31 - 40	4
41 - 50	5
51 - 60	6
61 - 70	7
71 - 80	8

adapted from Catchpole and Halpin (1987)

A daily ice severity index was determined by the multiplication of the daily ice severity code, **s**, by the lateness index, **d**. An example of how the daily index is obtained is provided in Figure 5.2 using a day from the log-book of the Prince of Wales I in its voyage to Hudson Bay in 1836. The daily ice indices were summed for each year to yield an annual ice severity index, the ISI, which is listed in Table 5.2. A summary of the steps taken to derive the ISI is given in Figure 5.4.

Figure 5.4: Stages in the Derivation of the ISI



from Catchpole and Halpin (1987)

Table 5.2: Annual Values of the ISI, 1751-1870

Year	0	1	2	3	4	5	6	7	8	9
1750		0	30	192	20	6	2	0	0	12
1760	22	8	28	26	4	44	3	44	5	0
1770	16	0	8	13	9	18	42	0	12	0
1780	15	4	0	0	5	0	4	0	28	0
1790	41	23	25	17	4	0	0	13	21	48
1800	18	20	8	3	24	20	12	18	19	27
1810	18	0	43	5	0	0	310	12	8	17
1820	11	4	30	77	9	10	6	18	24	15
1830	18	30	186	71	50	31	82	0	33	*
1840	*	*	46	13	23	17	12	24	22	0
1850	16	8	9	•0	24	56	48	20	8	12
1860	0	11	24	35	0	24	10	12	0	0
1870	32									

* Indicates no log-book for that year

5.4 The Ordinal Properties of the ISI

It is important to stress that the qualitative log-book descriptions were converted into ordinal data rather than interval or ratio data through content analysis. Ordinal data, which are ranking or rating data, are not as informative as interval or ratio data and therefore care must be taken during their analysis in choosing nonparametric statistical analyses which are applicable to this form of data. During the calculation of the ISI there were some arbitrary choices made and these have influenced the values of the ISI as well as the ordering of the years. Some examples of the subjectivity involved in determining the ISI include: the number of levels of sea ice severity; the code values of each level; the choice of modern conditions to determine lateness; the 10 day interval for each level of **d**; and the combination of **d** and **s** by multiplication. If any of the preceding decisions was altered, the values of the ISI would in turn be altered, and this might have resulted in changes in the relative ranking of some of the years.

5.5 Preliminary Analysis of the ISI

Several parameters of this investigation were run in a correlation analysis to test the independence of the ISI. Spearman's Rank Correlation Coefficient, r_S, was used to test for relationships between the ISI and the following variables: YEAR, the year of the voyage; DD, the date of departure from the last port in Britain; DES, the date of entry into Hudson Strait; and DAC, the duration of the Atlantic crossing. The null hypothesis for each test was that there was no association between the two variables, with an alternative hypothesis that there was an association between the two variables (α was set at 0.05).

It was found that there was no association between the ISI and any of the variables. The significance of these results is that the ISI is shown to be primarily a measure of year-to-year sea ice variability and not of seasonal variability of sea ice, i.e., the ISI is not significantly affected by the time of year the ships sailed. The lack of association between YEAR and ISI demonstrates that there is not a tendency for the ISI to increase or decrease with time. If such a tendency did exist, it could be an indication of climatic change over the 117 year period or it might be a basis for questioning the integrity of the ISI on the grounds that the quality of the log-books, as sources of sea ice information, changed significantly through time. The lack of relationship between DAC and ISI might be surprising because it might be expected that the presence of ice which besets a ship or necessitates avoidance would slow progress and result in a longer Atlantic crossing. There was no association for two reasons. Firstly, there usually was no ice encountered until the last few miles of the voyage, and thus the presence of ice was not a factor for the majority of the trip. Secondly, the ships had the large area of the Labrador Sea to manoeuvre in to avoid ice, until they reached Hudson Strait.

Chapter 6: The ISI Compared with other Historic Sea Ice Findings

Sea ice severity indices for the eighteenth and nineteenth centuries have been derived for seas adjacent to the Labrador Sea using the HBC ships' log-books. These are available for Hudson Strait (Faurer, 1981), for the eastern part of Hudson Bay (Catchpole and Halpin, 1987), and for the western part of Hudson Bay (Catchpole and Hanuta, unpublished manuscript) and in all three cases the record is from 1751 to 1870. In addition, Newell (1983) derived indices of annual sea ice severity in the Labrador Sea during the nineteenth century using a set of sources which did not include the HBC ships' log-books. This chapter will compare and contrast the indices derived in this study with those presented by Faurer (1981), Catchpole and Halpin (1987), Catchpole and Hanuta (unpublished manuscript), and Newell (1983).

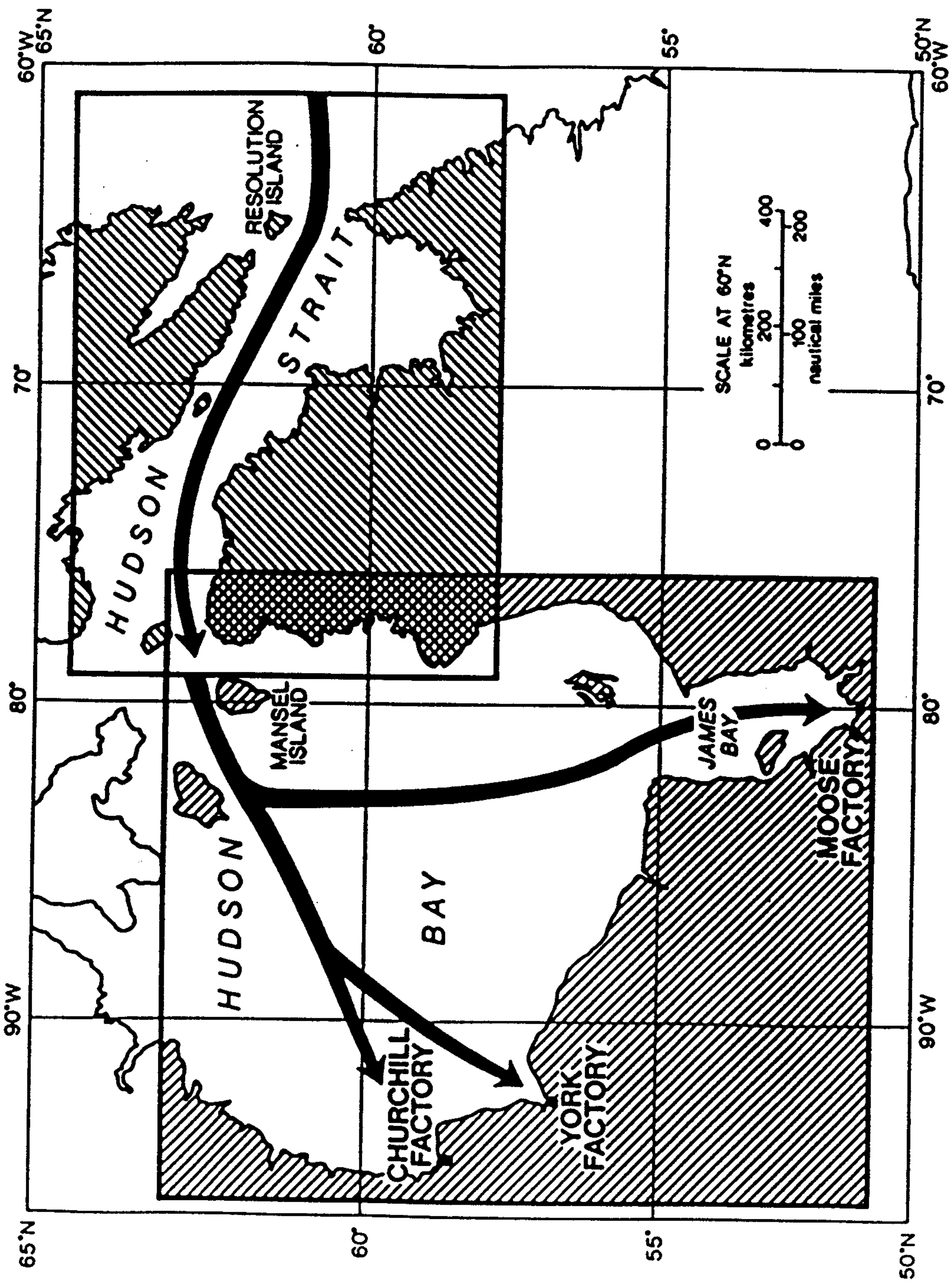
6.1 Comparisons with Hudson Strait Indices

A difficulty which confronts researchers when comparing the results of historic studies arises from the different sources of data, different time periods studied, and different methods used to obtain results. In the comparison of the ISI with Faurer's (1981) and Catchpole and Faurer's (1983) analysis of Hudson Strait at least part of this problem did not exist since both studies relied on the same HBC log-books as their data source. As a result, both studies share the same study period (1751-1870), and the geographic locations are adjacent. Faurer's pioneering study into ice conditions as revealed by log-book descriptions used a significantly different method to obtain a measure of the sea ice severity in Hudson Strait from the one used here to measure sea ice severity in the Labrador Sea.

Faurer took advantage of the fact that the HBC ships had very little room in which to manoeuvre to avoid ice in Hudson Strait. From this it was determined that "sea ice conditions exerted a major influence on the progress of ships during the westward passages [through Hudson Strait] and that the annual variations in the durations of the westward passages [*Da*] in days comprise annual indices of summer sea ice severity" (Catchpole and Faurer, 1983). This strong correlation between duration and sea ice severity did not exist in the Labrador Sea, and therefore a similar analysis was not applied in the derivation of the index in this region.

A difficulty which arose in the comparison of the ISI with the Hudson Strait index, *Da*, was that the two indices are not completely independent of each other. In the determination of the durations of the Hudson Strait passages, the ships were considered to have entered Hudson Strait when the crews first reported sighting Resolution Island, regardless of their location. In the development of the ISI the ships were not considered to have left the Labrador Sea and entered Hudson Strait until they rounded Cape Resolution (Chapter 2). As a result of this difference in definition, there was a small (in most cases) geographic overlap between the two study areas. This was a variable overlap ranging from a low of zero to a high of 25 days in 1816. The adjusted annual durations of the westward passages through Hudson Strait, *Da*, were tested for correlation, using Spearman's rank correlation coefficient, with the ISI. The analysis returned a correlation coefficient, r_s, of 0.265 (significant to .0039), and a coefficient of determination, r_s^2, of 7.0%. Despite the significance of the result, the correlation is not high enough to overcome the fact that *Da* and the ISI have some common study area. It is likely that if the geographic overlap were eliminated there would no longer be a significant correlation. The possible causes of this lack of correlation between the ice indices derived for two adjacent bodies of water is discussed in the next section.

Figure 6.1: HBC Supply Fleet Routes



6.2 Comparison with Hudson Bay Indices

Once the HBC ships entered Hudson Bay from Hudson Strait their routes diverged. One route was to the western shore of Hudson Bay, with the destination being either Churchill Factory or York Factory, the second route was to Moose Factory in James Bay (Figure 6.1). The analysis of historical ice severity in Hudson Bay was accordingly undertaken in two parts. The approach to Moose Factory was the basis for the estimation of ice severity in eastern Hudson Bay (Catchpole and Halpin, 1987), while the western approach to Churchill Factory and York Factory was used to develop an ice index for the western part of Hudson Bay (Catchpole and Hanuta, unpublished manuscript) using the same method.

The major value of the indices for Hudson Bay, Hudson Strait and the Labrador Sea, lies in their ranking of individual years, not in the numerical amounts obtained for each year. Since all of the indices are ordinal data, the indices for western Hudson Bay and eastern Hudson Bay were included in a Spearman's ranking correlation analysis along with the Hudson Strait index, *Da*, and the ISI for the Labrador Sea. All variables were tested for any interrelationships which could be exposed by this form of analysis. No significant correlations were found between any of the pairs of sea ice severity variables, other than the aforementioned ISI/*Da* correlation. It is particularly noteworthy that no significant correlation was observed between the two sets of Hudson Bay data.

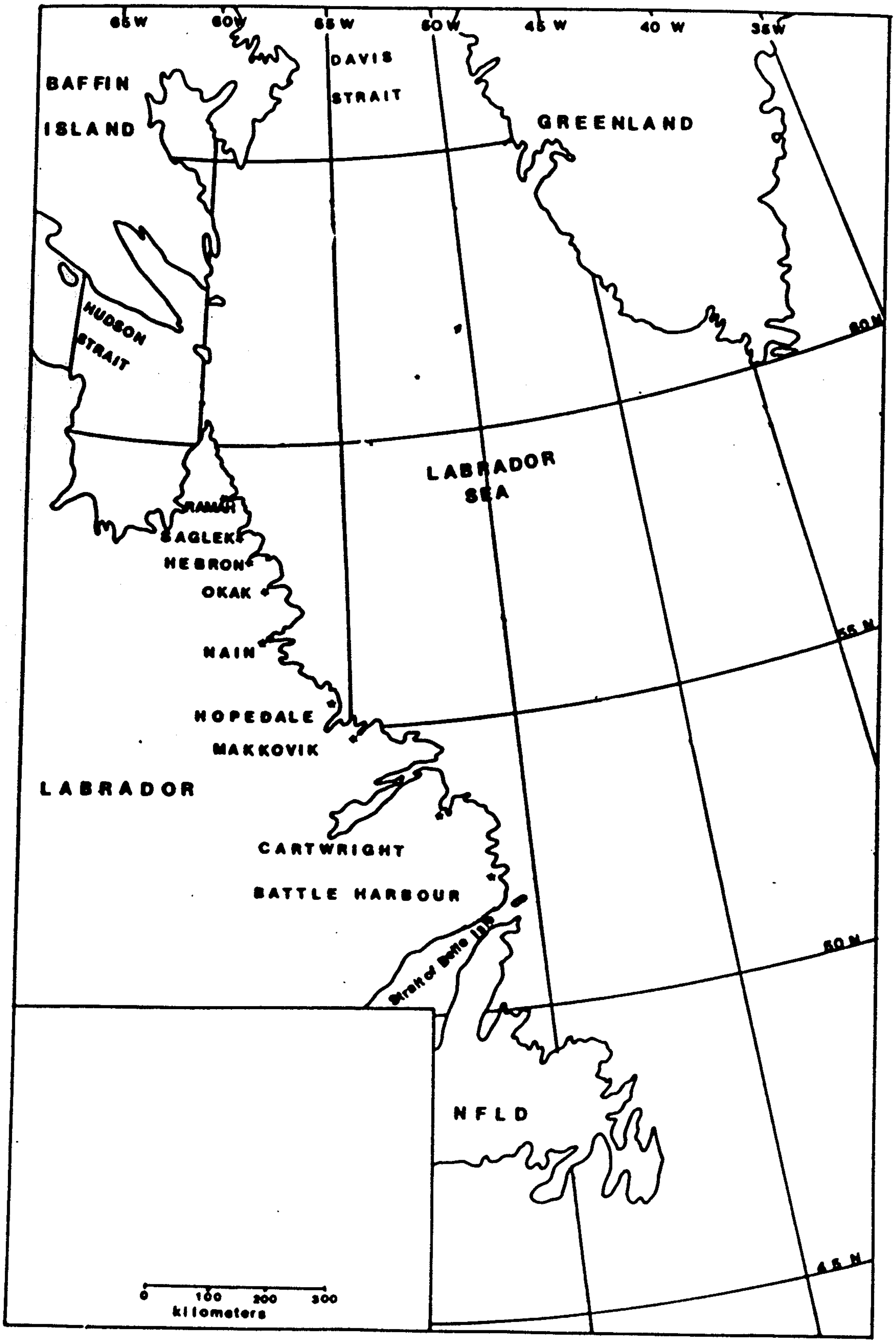
This finding stresses the complexity of the set of factors determining the patterns of summer sea ice dispersal. Prime among these are surface atmospheric circulation, sea currents and tides, and the seasonal regimes of the components of the surface energy balance. The contrasting sizes, orientations and shapes of Hudson Bay, Hudson Strait and the Labrador Sea create circumstances under which atmospheric circulation and water movement, in particular, have very different local effects on ice behaviour. This is true even within the confines of Hudson Bay. The early clearing of ice in western Hudson Bay is promoted by strong, persistent westerly and northwesterly winds that drive the ice towards the east and southeast. Obviously, these same wind conditions cause ice congestion in the east and promote there the late clearing of ice (Danielson, 1971).

6.3 Comparisons with other Labrador Sea Data

A reconstruction of summer ice conditions in the Labrador Sea in the nineteenth century by Newell (1983) was based on the log-books of whaling vessels sailing into Davis Strait, ice conditions for West Greenland compiled by Speerschneider (1931), and records from Moravian missions in Labrador. These independent measures of ice severity are potentially useful as a means of testing the validity of the ISI. However, this potential is diminished by differences between the two data sets, and differences between the two study areas. Although both this work and Newell's focus on the Labrador Sea, there is very little actual overlap in the study areas. Newell's data are from three separate sources each bearing on different parts of the sea. Over 54% of the ice data prior to 1870 came from the Moravian missions which give insight into ice conditions off the coast of Labrador. Since the missions were all located between the latitudes of 55°N and 59°N, displayed in Figure 6.2, most of the ice data are restricted to these latitudes. The data for southern Labrador, between 51°N and 55°N, are very sparse until after 1860. There are only eight ice references before 1860 and 17 in the 1860 to 1869 decade. The remaining ice references used by Newell (about 25% of total) describe conditions between the latitudes of 60°N and 63°N. On average, there are less than five ice references per decade (up to 1870) for this area. It appears that these ice descriptions refer to an area to the north and east of the ISI study area. Thus, although Newell's data describe ice conditions for the same general body of water, there is not an actual overlap of the specific locations of the ice data. The vast majority of ice severity descriptions used to produce the ISI were written to the north of the Moravian mission data, and to the south and southwest of the Davis Strait data.

There is a broad temporal overlap between the two studies. The Newell research covers all of the nineteenth century and does not extend back to the eighteenth century while the HBC data covers the period 1751 to 1870. This provides an overlap between the two data sets of 71 years from 1800 to 1870. This overlap period shrinks to 53 years when the 15 years of missing data in Newell's record and the three years of missing data from the HBC log-books are considered. The overlap period is reduced further to 50 years when the data listed in Newell's (1983) appendix are examined. Data referring to freeze-up conditions in the fall or ice conditions too distant geographically from the ISI study area were deemed unsuitable for comparisons. The overlap period of 50 years is sufficient for each set of data to provide a validity test for the other. The overlap period covers over 42% of the ISI record and nearly 59% of Newell's 85 year record.

Figure 6.2: Locations of Moravian Missions



Newell used data from Moravian missions in northern Labrador, as well as other sources to obtain his analysis of sea ice conditions in the Labrador Sea. The modern conditions which form the basis for Newell's analysis were the Sowden and Geddes' (1980) ice charts discussed in Chapter 2. Newell used the median ice edge to represent normal conditions as well as the maximum ice edge to represent modern extremes. By comparing the historical date of ice dispersal with each of these ice edge dates, Newell derived the following three levels of ice severity for the Labrador Sea in the nineteenth century:

++ The most severe ice condition was applied to years when the ice lasted later than the date of Sowden and Geddes' maximum ice edge.

\+ This was applied to years in which the last ice observed occurred between the dates of the median and the extreme ice edge.

\- This was applied to years in which the last ice observed occurred before the date of the median ice edge or when there was no evidence to indicate ice occurred later than the date of the median ice edge.

A major problem involved in the comparison of the ISI with Newell's data is that the two data sets are in different forms. The ISI ranks all years in terms of increasing summer sea ice severity, whereas Newell divided the years into three broad groups of sea ice severity. Newell's sources were generally less informative than the HBC log-books (for example, Newell had 122 ice references for the period 1800 to 1870, whereas the HBC log-books have 689 ice references for the same period), therefore he was not able to produce a numeric index or a ranking of the individual years. For a comparison of the two data sets it was not possible to convert Newell's broad groupings into a more informative level of data such as the ranking of years, but it was possible to divide the ISI* into three broad groups. The ISI represents a ranking of the sea ice severity of the Labrador Sea, ranging from the mildest conditions which were as mild as a modern mild ice year, to conditions which were more severe than present day extremes (Chapter 7). Between this wide range of conditions lie ISI values which are indicative of ice conditions approximately equal to present day norms and present day extremes. With the identification of the ISI value which represented modern norms, and the value which represented the modern day extremes, the ISI was divided into three groups similar to those that Newell used in his classification.

The ISI value which represents modern day normal ice conditions was determined by superimposing the sailing routes of the HBC ships over a map of Sowden and Geddes' median ice edge. An ISI of 5 was found to represent present day norms. An ISI of 10 was determined to represent modern day extreme ice conditions, by superimposing the route of the HBC sailing ships over a map of Sowden and Geddes' maximum ice edge. With the establishment of the ISI values which represent these present day ice conditions, the ISI was broken into the three groups of ice severity defined by Newell earlier.

It was found that 32 of the 50 years of overlap had ice conditions which Newell defined as more severe than today's extremes. Of these 32 years, 24 years were also considered more severe than present day extremes by the ISI. This is a statistically significant agreement, because the probability of a 24 year agreement in a random sample of 32 years is only 0.025. There were ten years in the overlap period which were classified by Newell as more severe than present normal, but less severe than present day extremes. Of these ten years, three were classified as more severe than normal by the ISI. An agreement of 3 years out of ten is not significant since there is a 0.22 probability of this occurring by chance. Newell assigned eight years to the category of milder than present normal, whereas the ISI only assigned three of those eight years to the same category. This is also insignificant by the significance standards of this study ($\alpha=0.05$), since the probability of three agreements in a random sample of eight is 0.089.

The statistical significance of the agreement between the two data sets in the more severe than present extreme category provides only a small measure of validity for both data sets. Two factors may have influenced this result. Firstly, although both data sets are labeled as measures of sea ice severity for the Labrador Sea, it is important to remember that each is only a measure of sea ice severity for the region of the Labrador Sea covered by the data, and in the absence of a more detailed analysis of conditions in the Labrador Sea, this severity cannot necessarily be extrapolated to the other study area. For this same reason, a direct contradiction between the two data sets over ice severity for an individual year, does not diminish the validity of one or both data sets. Secondly, the measure of validity is small because there is a statistically significant agreement in only one of the three groups. This, however, is the most important of the three groups in which to have a significant agreement, since, "for many years, sea-ice conditions may have been more severe than indicated, because most observations do not refer to a final clearing date" (Newell, 1983).

Through a closer examination of the most extreme disagreements between the years selected by the two data sets, it can be determined if the data for the two areas do contradict each another, indicating different ice conditions, or if they point to deficiencies from a lack of information. There were six years in which ice conditions for the Labrador Sea were considered more severe than present day extremes by Newell's data and considered milder than present day normals by the ISI. In one example, 1811, the ISI was found to be zero, and in fact there was no ice sighted in the Labrador Sea by the HBC supply ship that year. This was an unusual year for the HBC ships, however, because this was the latest that the HBC convoy ever left Britain (July 26) and the ships did not enter Hudson Strait until September 6, which was also the latest on record. In the most extreme years in modern record, there is an ice free approach to Hudson Strait by late August; therefore, the ice free evidence obtained by the HBC crews in 1811 does not contradict the evidence from the Moravian missions, as the ice conditions could have been, and probably were, more extreme than modern record. In 1803, however, there is a direct contradiction between the two indices. In 1803, the crew of the Prince of Wales I did not sight ice until after they had seen Resolution Island on July 25. The ice was described as straggling, and did not provide them with any difficulty when they entered Hudson Strait a few hours later. The Moravian mission ship that reached Okak mission on August 10, however, encountered severe ice and was delayed for three weeks off the Labrador coast by this ice. A difficulty that arises here is that the coast of Labrador has an added influence that does not affect ice conditions in the approach to Resolution Island. The current which removes ice from Hudson Strait (Figure 2.12) may have influenced the ice conditions observed by the Moravians in years such as 1803. In these years ice was observed near the Labrador coast, but not at the approach to Resolution Island. There were eight years in which Newell classified the ice conditions as milder than present normal. Only three of these eight years were classified by the ISI as less severe than present normal. In three of the five years of disagreement there is ice sighted by the Moravians, but it is too early in the year to justify a more severe ice rating. There is no evidence of ice clearing early to contradict the ISI which had rated these years as more severe than present extremes. In two years, 1822 and 1838, there appears to be a direct contradiction between the two indices. The Hopedale mission reported no ice in sight on July 18, 1822 although 600 kilometres to the north the Prince of Wales I, encountered heavy ice on July 22, 23, and 24. The crew forced the ship through ice July 22 and July 23, and had to grapple to ice on July 24. After an examination of ice clearing dates (Figure 2.11) it is apparent that in the 1822 example there is not a direct contradiction. The ice clearing date in years of late ice retreat on the Labrador coast is June 25 which is 23 days earlier than the date on which Hopedale Mission reported no ice in sight. In 1822 ice could have cleared up to three weeks later than present day extremes and this does not disagree with the findings of the ISI.

The disagreement analysis provides evidence which indicates that if years of insufficient data were excluded from the original analysis, there would be a significant agreement among all three groups. The analysis does provide evidence indicating that the area investigated by Newell has similar ice conditions to the area covered by the ISI, particularly in years of very late ice retreat (two case studies of severe ice conditions will be discussed in more detail in Chapter 7). Although the two regions have similar ice conditions, they are not identical because the Labrador coast has the added influence of ice from Hudson Strait. Another difference was uncovered by Crane (1978) in his analysis of ice clearing. Crane detected two patterns of ice retreat, which he termed early and late (Figure 2.10 and Figure 2.11). Both patterns of ice retreat in the route of the HBC sailing ships (Figure 2.1) are similar, except, of course, the route is ice free three weeks earlier in the early pattern. The Labrador coast, however, shows two different patterns of ice retreat. In the years with early ice retreat the ice clears from east to west. In the years with late ice retreat there is a large shore lead that opens three weeks before the entire sea is clear. The HBC log-book data, and the methodology involved in the development of the ISI both receive a measure of validity, but the main importance of the ISI in conjunction with other Labrador Sea data is that it supplements the knowledge of historic ice conditions by supplying evidence for a different portion of the Labrador Sea.

Chapter 7: The Relationship between Volcanic Dust and Sea Ice Severity

Benjamin Franklin was probably the first person to question the possibility that volcanic dust affects climatic conditions when he wondered if the "dry fog", dust produced by volcanic eruptions in 1783, was responsible for the cold winter which occurred in western Europe and eastern North America in 1783-1784. Since then there have been many theories proposed, and studies undertaken to investigate the influence, if any, of volcanic dust on climate. "The effect is clearly likely to be greatest in high latitudes [such as the Labrador Sea area], where the always low angle of incidence of the solar beam implies long paths through any dust layers, and where ... production of more ice on Arctic seas should be expected to be a common consequence of great volcanic dust veils..." (Lamb, 1972).

The volcanic dust-climate theory is based on the assumption that dust particles in the atmosphere influence the intensity of both incoming solar radiation and outgoing terrestrial radiation. This implies that the presence of a large quantity of volcanic dust in the atmosphere will have a significant effect on the earth's radiation balance. The microscopic size of the dust particles causes them to have a far larger influence on the incoming shortwave radiation than on the outgoing longwave radiation. Theoretically, the result is a "reverse greenhouse effect", which is presumed to cause a global-scale lowering of surface temperature (Lamb, 1970). As there were several major eruptions during the period 1751 to 1870, it was decided to determine if there was a noticeable signal of volcanic activity in the sea ice conditions of the Labrador Sea.

7.1 Identification of Major Eruptions

It is well established that the volcanic eruptions capable of influencing global weather conditions are the explosive eruptions which inject large quantities of dust into the stratosphere. Most effective in this regard are those located in the equatorial latitudes between 20°N and 20°S. These inject dust initially into the Hadley cell and the upper westerlies and are able to diffuse this dust into both hemispheres causing a global dust veil. Eruptions occurring polewards of 20° latitude are able to create dust veils that are limited to the hemisphere in which the eruption occurred. The consequence of these various restrictions is that only a very small number of the eruptions that occurred between 1751 and 1870 had the capability to have influenced sea ice severity in the Labrador Sea. The first task in this investigation is to identify these major eruptions. The data sources on which this search is based are the dust veil index, DVI, devised by Lamb (1970), and the volcanic explosivity index, VEI, devised by Newhall and Self (1982).

a) The DVI

In his classic study of volcanic dust, Lamb (1970) devised a measure of the intensity, longevity and extent of dust veils produced by over 280 eruptions that occurred since 1500 A.D. This dust veil index was based on instrumental and historical evidence including the depletion of direct solar radiation, the temperature lowering in the middle latitudes, the quantity of solid matter dispersed as dust, and the extent and duration of the optical effects produced by the dust. Lamb developed three different formulae to calculate the DVI for all known eruptions since 1500 A.D. The choice of the formula used would depend on the information available. Each formula contains a coefficient which was designed to yield an index value of 1000 for the 1883 eruption of Krakatau, thus making Krakatau the standard for comparison.

In the development of the DVI formulae, Lamb considered three main properties of volcanic dust veils which would have meteorological significance. The first factor is density or opacity. This would be dependent upon the amount of dust injected into the atmosphere by the volcano. The second factor is the maximum extent, or geographic area, covered by the dust veil. This factor was included to account for the latitude of the volcanic eruption as eruptions occurring within the tropics will spread dust to cover a greater area of the globe than an eruption in a polar region. The third factor is duration of the dust veil. The total life of the dust veil depends upon the entry of dust into the stratosphere. The higher the dust is ejected, the longer its residence in the atmosphere.

Lamb assigned a DVI to all known eruptions from 1500 A.D. to the present. The highest DVI of 4000 was assigned to the 1835 eruption of Coseguina, while the 1815 eruption of Tambora was rated second highest with a DVI of 3000. The three highest DVI on record occurred within the 1751 to 1870 time period. The DVI for volcanic eruptions in the period 1751 to 1870 are presented in the graph in Figure 7.1.

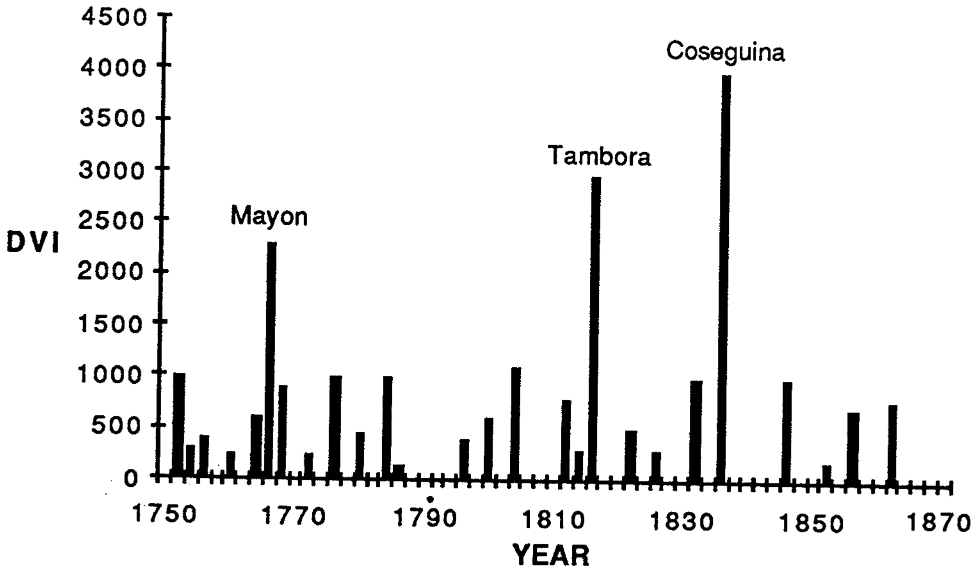


Figure 7.1: Lamb's Dust Veil Index 1751-1870

b) The VEI

The volcanic explosivity index, VEI, devised by Newhall & Self (1982) is a measure of a volcano's explosivity. Over 8000 eruptions since 1500 A.D. were assigned a VEI value on a scale of 0 to 8 with 8 as the most severe. This is based on the volume of material ejected, the rate at which the material was ejected, the destructiveness and the dispersive power of the eruption. One important feature of the VEI is that it does not consider latitude of the eruption or elevation of the eruption column. These factors influence the spread of the dust veil which in turn determines its ability to modify weather conditions. As a result, caution must be used when dealing with the VEI in climate-volcanic dust relationships. Newhall & Self assigned a VEI value of four or greater to 31 eruptions during the period 1751 to 1870. Of these 31 eruptions only five were given a VEI of five or more, and the most severe VEI of seven was assigned to the 1815 eruption of Tambora. The five volcanoes with VEI values of five or greater are listed in Table 7.1 along with the other eruption years selected for this study. The criteria applied in the selection of major eruptions were:

1) eruption located north of 10°S;
2) a DVI greater than or equal to 1000;
   and/or
3) a VEI greater than or equal to 5.

7.2 The Volcanic Dust - Sea Ice Analysis

The analysis technique employed in this study is an adaptation of superposed epoch analysis. Mass & Schneider (1977), Taylor *et al.* (1980), and Lough & Fritts (1987) among others have used this technique in their volcano-climate studies. This analysis has mainly, though not exclusively, been applied to records of mean annual temperatures. The analysis commences with the identification of major volcanic eruption years and is then applied to a finite interval of years before and after the eruption. In most studies this interval has ranged from a nine year period to a 20 year period centred on the eruption year. The mean annual temperatures in the individual years preceding and following the eruption year are next identified and tabulated. The table is completed by incorporating similar temperature data from other stations used in the analysis. The analysis then determines the mean annual temperature for each of the years before and after an eruption. The various applications of superposed epoch analysis differ according to:

a) the definition and selection of major eruptions;
b) the method used to normalize mean annual temperature in order to eliminate the effect of long term variations;
c) the methods used to test the significance of the differences between the mean and the years before and after an eruption.

The eruption years selected for this study were chosen with both the VEI and DVI as the main selection criteria. The first criterion was that all the eruptions were situated at a latitude north of 10°S because these alone were likely to have created a dust veil in the Northern Hemisphere. All eruption years with a DVI of 1000 or larger were chosen as well as all years with a VEI of 5 or larger, yielding a total of ten eruption years (listed in Table 7.1). The period of analysis selected in this study was the nine years extending from the fourth year preceding the eruption to the fourth year following the eruption. The ISI for each nine year eruption period is given in Table 7.2.

In previous studies, once the data were tabulated, the mean value for each of the nine years, or columns, was calculated, and these means were compared with each other statistically to determine if there was a volcanic signal. However, as discussed in Chapter 5, the ISI are ordinal data, not interval or ratio, and as a result the mean value is not a valid statistic for comparisons. It is here, in the test for a significant volcanic signal, that this analysis differs fundamentally from previous superposed epoch analyses.

To test for a significant volcanic signal appearing in any of the nine years, the statistical distribution of the ISI must be defined. The distribution is hypergeometric and so the data had to be redefined in terms of the hypergeometric random variable (Table 7.3). This probability distribution is similar but not identical to the binomial for the population size of this study. Whereas the probability of success remains the same as each sample is selected for the binomial, the hypergeometric probabilty function reflects the changing probabilities of success

Table 7.1: Eruption Years Included in Study
The Selection was based on a DVI greater than or equal to 1000 and/or a VEI greater than or equal to 5.

Year	Volcano	Location		DVI	VEI
1752	Little Sunda Is.	8°S	118°E	1000	n/a
1755	Katla	63.5°N	19°W	n/a	5
1766	Mayon	13.5°N	123.5°W	2300	4
1775	Pacaya	14°N	91°W	1000	n/a
1783	Laki/	64°N	18°W	1000	4
	Asama	36.5°N	138.5°W	(total veil)	
1803	Cotopaxi	1°S	78°W	1100	n/a
1815	Tambora	8°S	118 °E	3000	7
1822	Galunggung	7°S	108°E	500	5
1835	Coseguina	13°N	87.5°E	4000	5
1854	Sheveluch	57°N	161.5°W	n/a	5

Table 7.2: ISI for the Eruption Year Periods, from Fourth Year Preceding to Fourth Year Following each Eruption
The ten most severe ISI are printed in bold-face.

Eruption Year, E	- 4	- 3	- 2	- 1	E	+1	+2	+3	+4
1752	*	*	*	0	30	**192**	20	6	2
1755	0	30	**192**	20	6	2	0	0	12
1766	28	26	4	44	3	44	5	0	16
1775	0	8	13	9	8	42	0	12	0
1783	0	15	4	0	0	5	0	4	0
1803	**48**	18	20	8	3	24	20	12	18
1815	0	43	5	0	0	**310**	12	8	17
1822	8	17	11	4	30	**77**	9	10	6
1835	30	**186**	**71**	**50**	31	**82**	0	33	*
1854	16	8	9	0	24	**56**	**48**	20	8

* indicates no ISI available for that year

as each sample is selected. The statistical means of each year could not be used because this variable is defined in terms of *successes* and *failures*. For a perfect, or maximum response in terms of a volcanic signal in any year, the ten most severe ice years, ranked by the ISI (Table 7.4), would have to all occur within that year. These ten severe ice years were considered *successes* if they occurred in that year. The probability of all ten severe ice years, or successes, appearing in a random sample of ten is less than one in eighty-nine trillion. The hypergeometric equation and probabilities of all the possible different numbers of successes for samples of size 9 or 10 are listed in Table 7.3.

From the list of ISI values for each nine year volcanic period in Table 7.2 it was found that five of the ten most severe ice years occurred in YEAR+1. This is highly significant as the probability of five of the most severe ice years occurring by chance in YEAR+1 is 3.003×10^{-4} (about 1 in 3300). To put this statistical probability in perspective, a probability of .05 (or 1 in 20) is normally considered significant. None of the other eight years demonstrated a significant response. YEAR-2 had the second most successes with two, in a sample size of nine which has a probability of occurring by chance of 0.142, or approximately 1 in 7.

Previous studies, such as Mass and Schneider's (1977) and Lough and Fritts' (1987), used different criteria in the selection of the eruption years analyzed. To further emphasize the significance of the results of this study, and demonstrate that these results were not biased by the selection of the eruption years, the same statistical analysis was applied with the use of the eruption years selected by Lough & Fritts between 1751 and 1870. This analysis was repeated with the eruption years selected by Mass & Schneider. In both analyses the only significant result was in YEAR+1. There were four severe ice years in YEAR+1 out of the nine years selected by Lough & Fritts. The probability of picking four severe ice years in a random sample of nine is less than three in one thousand. The YEAR+1 response has a higher significance using the Mass & Schneider eruption years because four of the ten most severe ice years appear in the five years selected by their criteria. The probability of this happening by chance is about 0.00013, or 1 in 7500.

Table 7.3: Hypergeometric Equation and Probabilities

Equation:

$$P(y) = \frac{C^k_y \, C^{N-k}_{n-y}}{C^N_n}, \quad y=0,1,2, \ldots n \qquad \text{where} \quad C^k_y = \frac{k!}{y!\,(k-y)!}$$

For The ISI data, where:

Population Size, N=117; Sample size, n=9 or 10;
Total possible number of successes, k=10;
Number of successes, y=0, 1, 2, ...10;
P(y)= probability of y successes.

Probabilities:

y=	P(y), n=10	P(y), n=9
0	0.39393389	0.43413126
1	0.40197338	0.39466478
2	0.16444365	0.14207932
3	3.508×10^{-2}	2.626×10^{-2}
4	4.255×10^{-3}	2.703×10^{-3}
5	3.003×10^{-4}	1.575×10^{-4}
6	1.215×10^{-5}	5.047×10^{-6}
7	2.670×10^{-7}	8.240×10^{-8}
8	2.861×10^{-9}	5.830×10^{-10}
9	1.200×10^{-11}	1.211×10^{-12}
10	1.121×10^{-14}	

Table 7.4: The Ten Most Severe Ice Years in the Labrador Sea

Rank	Year	ISI
1	1816	310
2	1753	192
3	1832	186
4	1836	82
5	1823	77
6	1833	71
7	1855	56
8	1834	50
9	1799	48
9	1856	48

Another interesting feature of this analysis is that the ice conditions were not significantly more severe in the second and third years after eruptions. Previous studies, such as Mass & Schneider's, have found a small but significant volcanic signal of temperature depression in the second year after an eruption. Ice conditions of the Labrador Sea do not show significant severity in the second year after an eruption. The ninth most severe ice condition (1856), is the only one of the ten most severe ice years to occur in the second year after an eruption. This is not a significant response as the probability of one of the most severe years being selected by chance is over 0.4.

7.3 Case Studies: 1816 and 1836

Two case studies are presented to reconstruct in detail the severe ice conditions encountered in the Labrador Sea as well as corresponding cold weather from other areas of the Northern Hemisphere following major eruptions. The first case study year, 1816, was chosen because it followed the year with the largest VEI, it produced the most severe ISI, and is also a year of well documented climatic anomalies in other areas of North America and Europe. The second case study year, 1836, was chosen because it followed the year with the highest DVI. The year 1836 is an interesting study because it is a year of widespread cold conditions and it followed the 1835 eruption of Coseguina.

a) 1816

The year 1816 was marked by unseasonably cold weather throughout most of the Northern Hemisphere. This unusual weather is attributed by many climatologists to the April 1815 eruption of Mt. Tambora. Mt. Tambora, located at 8° S, on

Sumbawa Island, Indonesia, probably produced the largest ash eruption in recorded history, with total ejecta estimated at between 150 and 200 km^3 (Rampino and Self, 1982). Newhall and Self (1982) assigned a VEI of 7 to Tambora. This was the highest VEI assigned to the set of 8000 eruptions which they ranked. Lamb assigned a DVI of 3000 to Tambora and this was the second highest value that he assigned with only the 1835 eruption of Coseguina being ranked higher.

Europe and northeastern North America received particularly harsh weather in the summer of 1816 and Post (1977) identified the years 1816-1819 as the period of the "last great subsistence crisis of the western world". Post attributed this subsistence crisis to the extremely cold weather of 1816 and 1817 by highlighting cold weather and poor harvests (or complete crop failures) throughout Europe, north-eastern United States and Canada. An example of the poor summer is exhibited in the grape ripening dates of France. French historians have extracted grape ripening dates since 1601, and 1816 was found to be the year with the latest ripening date on record. Another example occurs in the English midlands, which have temperature records dating back to 1698. July 1816 registered the lowest mean temperature for that month for the entire period of observation. There was also unseasonably cold weather and poor harvests in Belgium, The Netherlands, Germany, Switzerland, and several other regions of Europe (Post, 1977).

Cold weather and poor crops were evident in eastern North America in 1816, and Stommel and Stommel (1979 and 1983) have termed the year 1816 as the 'year without a summer'. They searched through old newspaper reports, journals, and diaries in eastern North America to document occurrences of severe weather. Their research revealed there were frosts in every month of 1816 in New England, and the "meteorological record for New Haven which had been kept by the president of Yale College since 1779 records June 1816 as the coldest June in that city" (Stommel and Stommel, 1983). Baron and Gordon (1985) found that the length of the growing season in eastern Massachusetts in 1816 was the shortest on record (1745 to present) at about 50 days, compared to a normal of about 155 days.

HBC post journals and ships' log-books have provided evidence of severe cold and extreme ice conditions for the summer of 1816 in the Hudson Bay area and approaches. For eastern Hudson Bay it was found the "summers of 1816 and 1817 were not only colder than those on modern record, but were exceptionally severe even for this period" (Wilson, 1985a). During the summer of 1816, the east coast of Hudson Bay experienced arctic conditions and the mean daily temperature at

Great Whale was nearly 6°C below the 1941 to 1970 normal (Wilson, 1985a).

Some examples of the entries in the post journals that provide evidence of the severe summer of 1816 in eastern Hudson Bay follow:

> The gardens at (Great) Whale River have not produced a single root of vegetables of any kind whatever.
> *(HBCA, PAM, Fort George journal, B77/a/3, fol. 5, October 10, 1816.)*

> None of the grass or anything else has come to perfection this season. Continual frost and snow throughout the summer, has been a great impediment to all kinds of vegetation. Not so much as a berry of any kind is scarcely to be seen, which on more favourable seasons are found here, to grow spontaneously in great abundance.
> *(HBCA, PAM, Fort George journal, B77/a/3, fol.3, September 27, 1816.)*

> I have got no vegetables whatever, the plants that were sent so opportunely from Moose last summer are no larger than when planted, as for Potatoes, there is not the smallest branches to see above the ground.
> *(HBCA, PAM, Eastmain journal, B59/a/96, fol. 10, October 13, 1816.)*

> The repeated frosts has destroyed the potatoes. The leaves are all gone, and nothing but the naked stalks remain.
> *(HBCA, PAM, Naosquiscaw journal, B.143/a/15, fol. 10, September 4, 1816.)*

> I set to mowing down the oats, barley in the Park, as the season is pretty far spent, but the grain has come to nothing - the straw however will come in for the cattle.
> *(HBCA, PAM, New Brunswick journal, B145/a/34, September 20, 1816.)*

The above journal entries are all from posts located in the eastern part of the Hudson Bay region and the extreme cold that was experienced in the summer of 1816 was only noticed in this region. The ships' log-books reveal that 1816 had the seventh most severe summer sea ice conditions in the eastern part of Hudson Bay (Catchpole and Halpin, 1987) but the post journals from the western shore of Hudson Bay did not report unusually cold weather. The ice index derived for the western part of Hudson Bay was zero. This indicates that in 1816 the ice in the western part of the Bay was no more severe than that encountered in 1969, the year associated with the most severe ice in these waters in the period of the modern record (Catchpole and Hanuta, unpublished manuscript).

Evidence of severe summer sea ice conditions in 1816 in the Labrador Sea was uncovered by Newell (1983) using the Moravian missionary records. Newell found that the ice clearing in 1816 was the latest during his period of study, with the ice clearing 11 weeks later than present day normal. This clearing date was more than seven weeks later than the present extreme and was the latest clearing date ever recorded. There is evidence that ice may have remained on the coast of Labrador until freeze-up.

The HBC log-books support Newell's finding and indicate that 1816 was indeed the year in which ice conditions were the most severe on record in the Labrador Sea. Table 7.4 shows that 1816 had the largest ISI of all 117 years ranked with a value of 310 which is over 50% larger than the next highest year. Figure 7.2 is a graphic illustration of how 1816 compares with the years 1811 to 1819. In 1816 the Prince of Wales was beset by ice for 21 days while in the Labrador Sea. This was more than twice the number of days any other ship was beset in the period of record. In this year the Prince of Wales left port in the Orkney Islands 16 days earlier than normal, yet she did not round Cape Resolution and enter Hudson Strait until seven days later than normal. The 1816 voyage from Orkney to Hudson Strait was the longest Atlantic crossing during the period 1751 to 1870 requiring 54 days, compared to the average crossing of 31 days.

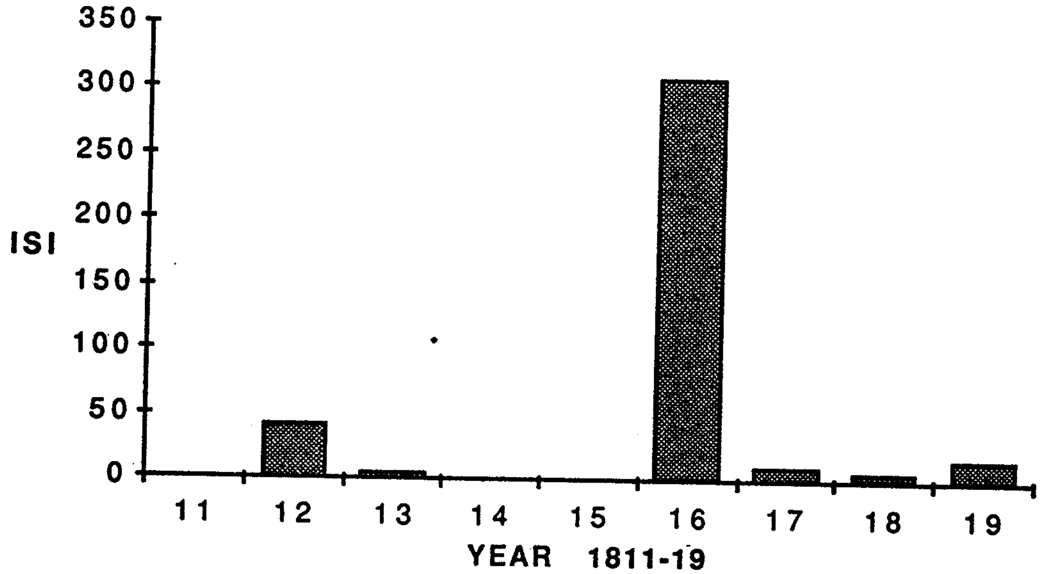


Figure 7.2: The ISI from 1811 to 1819

b) 1836

In 1835 the volcano Coseguina, in Nicaragua (13° N, 87.5° W) erupted. Lamb assigned Coseguina a DVI of 4000, the highest index assigned to any volcano. Recently, however, doubt has been cast on this ranking, most notably from the lack of a large volcanic signal in polar ice cores (Hammer, Clausen and Dansgaard, 1980). Newhall and Self (1982) gave Coseguina a VEI of 5, which is indicative of a very large eruption but still lower than the VEI of 7 assigned to Tambora and 6 assigned to the eruption of Krakatau in 1883. Although there is some doubt about the size of the eruption of Coseguina, and whether or not the dust from the eruption itself significantly influenced the climate of 1836, there is much evidence that suggests that 1836 was a year of extreme cold.

The northeastern United States suffered cold weather in 1836. Baron and Gordon (1985) found in their reconstructed winter temperatures for Providence, Rhode Island, that 1836 had the lowest temperature of all years on record from 1830 to present. Another example of the cold weather of 1836 occurred when George Bach was ordered to sail to Repulse Bay, at the head of Roes Welcome Sound between Southampton Island and the Kewatin Coast. His ship, the Terror, was beset by thickening pack ice in September and the crew were unable to free the ship until the midsummer of 1837. The exceptionally stormy and severe weather encountered in the United States and Europe prompted an article published by the Smithsonian Institute entitled "Certain Storms in Europe and America: December, 1836" (Loomis, 1859).

Hanuta (1986) found evidence of exceptionally severe ice conditions and cold and stormy summer weather in Hudson Bay in 1836 using the HBC log-books and post journals. The Prince

Rupert encountered very late ice in September in Hudson Bay, as well as stormy and cold weather. The ship was unable to reach York Roads because of the weather and had to anchor nearby. Here the ship suffered gales and snow and developed a problem with icing, as she became coated in ice from freezing spray. The ship was described in the log-book as "a mass of ice" and later as "a complete Ice berg these last two days" (HBCA, PAM, Prince Rupert log-book, October 1, 1836, C.1/930). The cold weather and stormy conditions drove the ship from her anchorage resulting in the loss of two of her three anchors and the third being broken. Finally, the officers decided to abort the voyage and return to England to avoid further damage despite being so close to their destination. The ice severity index determined for the western portion of Hudson Bay was the most severe in the period of record of 1751 to 1869 (Catchpole and Hanuta, unpublished manuscript).

Newell (1979) found that whaling ships could not reach the northwater of Baffin Bay because of severe ice conditions in 1836. Newell (1983) also found that ice conditions in the Labrador Sea for the year 1836 were more severe than the present day extreme, and considerably more severe than the normal for the nineteenth century. In fact the captain of the mission ship arriving that year "described the voyage as the most hazardous since 1816" (Newell, 1983). Journal accounts from Hopedale Mission reported that the ice broke up on July 14, the latest date on their record. Later, on August 24, mission ships reached Hopedale after trouble with ice (Newell, 1983).

Again Newell's findings for the Labrador Sea corroborate the results of this study. The year 1836 does indeed appear to be a year of late ice retreat, although not as severe as 1816. The ISI for 1836 was 82 which ranks as the fourth most severe of the 117 years of record. Before rounding Cape Resolution and leaving the study area, the Prince of Wales I was beset in ice for four days from July 28 to July 31 when she found open water and entered Hudson Strait on August 1. In only three other years were ships beset by ice on more than four days in the Labrador Sea. The Prince of Wales, in 1836, was the only ship in this study to be damaged by ice while in the Labrador Sea. The Prince of Wales had her rudder broken by the ice and she was nearly wrecked as the ice almost drove her onto the rocks near Button's Islands. The rudder was broken at about 11:00 pm on July 27 and was not repaired until about 11:00 am on July 31 - a total of nearly 84 hours (3.5 days) without a rudder. The following excerpts from the log-book of the Prince of Wales demonstrate the peril the ship was in:

> July 27 at 5 close in with the land - the ice close keeping us off the rocks and the current setting bodily on them - the ship quite unmanagable among the ice

> the ship took the ... forcing her bow upon the ice and at the same time **twisting the rudder from the sternpost - the main piece being completely broke about 10 feet from the head.**
>
> At midnight beset among the ice driving towards the land.
>
> July 28 ... continued driving along the margin of the islands sometimes being no more than the ship's breadth from those immense perpindicular rocks - driving along with alarming velocity, the ice winding and running in every possible direction.
>
> July 30 At 2 an enormous body of heavy field ice, being evidently propelled by a very strong current came rushing down to leeward sweeping us, and the ice to which we grappled, away to the SE at the rate of 4 knots - ship beating very violently up against it.
>
> (HBCA, PAM, Prince of Wales I log-book, July 27-30, 1836, C.1/831)

Figure 7.3 shows the ISI from 1830 to 1838, which includes the eruption years 1835 and 1831 (according to Mass & Schneider's definition). One notable feature displayed by the graph is that the ice conditions appear severe throughout the eighteen-thirties. Only 1837 has an ISI value which is below the median of 13, and four of the ten most severe ISI years occur between 1832 and 1836. There is a noticeable increase in sea ice severity in the year following an eruption.

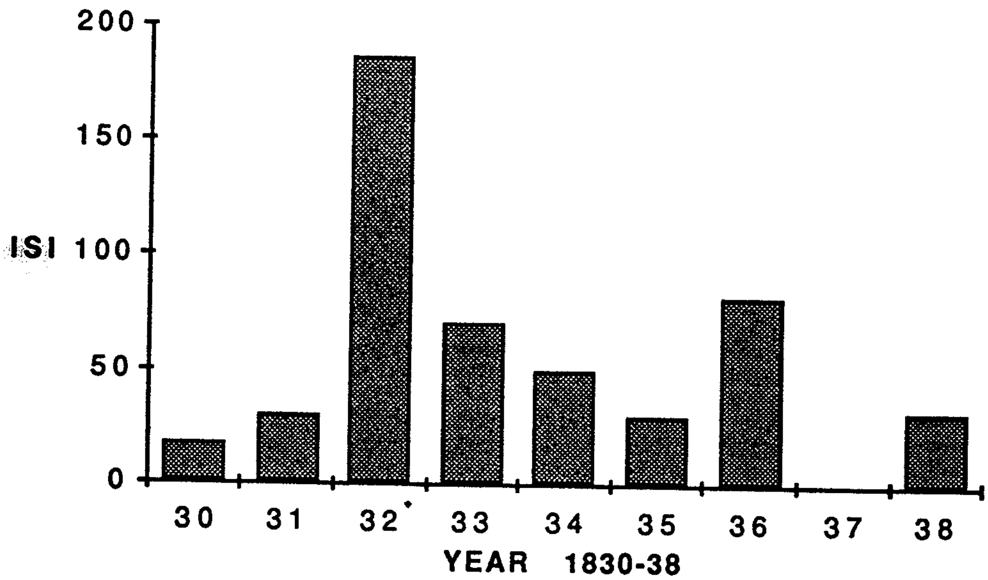


Figure 7.3: The ISI from 1830 to 1838

7.4 The Relationship between Atmospheric Circulation and Severe Ice Conditions in the Labrador Sea

The ISI for the Labrador Sea supports the evidence from other sources and other areas of the world that the years 1816 and 1836 suffered extremely cold and severe summers. Not only were these years severe in comparison with other years in the period but they were much colder than our present extremes.

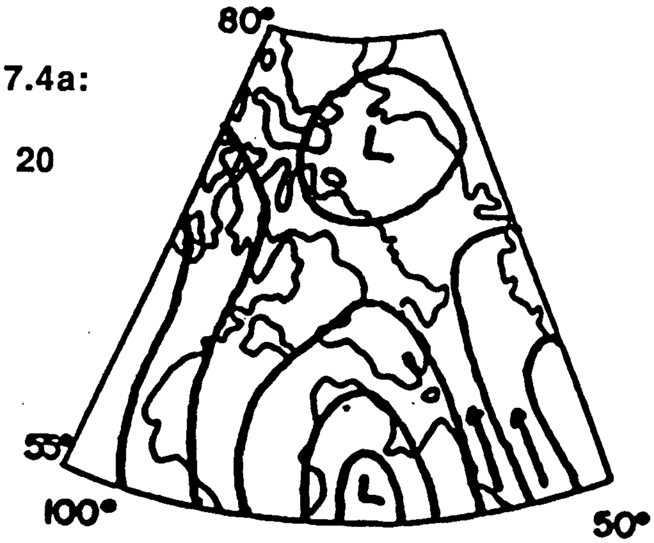
There is a distinct and statistically valid volcanic signal shown by late ice clearing conditions in the Labrador Sea in the year immediately following a large eruption. From the very high significance of this volcanic signal on sea ice conditions it appears there is a relationship between atmospheric circulation and volcanic dust. Since the rate of pack ice clearing is largely a function of atmospheric circulation, there appears to be a significant relationship between volcanic dust and atmospheric circulation. Although it is beyond the scope of this study to speculate on the specific mechanisms which affect atmospheric circulation, a brief description of the synoptic circulation patterns which affect ice clearing in the Labrador Sea is in order.

As discussed in Chapter 2, Crane (1978) identified two distinct patterns of ice retreat in the Labrador Sea which he termed *early* (Figure 2.10) and *late* (Figure 2.11), with these patterns having different synoptic circulation patterns. Crane found that a key difference between years with early ice retreat and years with late ice retreat was that "the years of early ice retreat have more southerly airflow" (Crane, 1978). This more frequent southerly airflow found in the early ice retreat years is due to a more frequent occurrence of a low over Foxe Basin (Figure 7.4a) or a low over northern Quebec (Figure 7.4b). The increased frequency of southerly airflow accelerated the clearing of ice in two ways. Firstly, the advected sensible heat from the south increased the temperature and thus increased the rate of ablation of the ice. The second way in which ice retreat was accelerated occurred because of an increased pressure gradient which resulted in stronger winds that aided in removing the ice. In the years where ice retreat was late, there was a less frequent occurrence of the lows in Figure 7.4, and thus less warm southerly airflow. The lower temperatures resulted in a slower rate of ablation and the lower pressure gradient also meant that winds were weaker and ice removal was slowed. Crane also found that the difference between late and early ice retreat years can ultimately be attributed to the relative displacement of the 700 millibar trough over Baffin Island. He found that in years with a late pattern of ice retreat the trough was displaced more to the east, over Baffin Bay. In the years of early ice retreat the trough was displaced much less to the east, over Baffin Island. The eastward displacement of the trough promotes the influx of cold north and northwest winds over the Labrador Sea. When the trough is displaced toward the west these are replaced by the warm southerlies.

Figure 7.4: Most Frequent Synoptic Types with Southerly Airflow

Figure 7.4a:

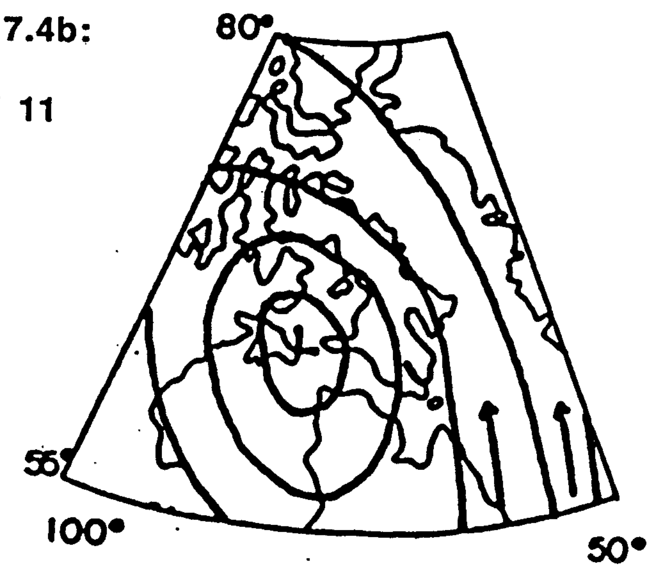
TYPE 20



Most Frequent synoptic types with southerly airflow (Type 20 above and Type 11 below) for June-August in years with early ice retreat. (from Crane, 1978)

Figure 7.4b:

TYPE 11



Chapter 8: Icebergs in the Labrador Sea

Icebergs have been left for separate study because they are different from pack ice in almost all respects, from genesis to size, distribution and behaviour. The presence of icebergs and their distinctness was noted by the HBC crews in their voyages across the Labrador Sea. Icebergs were recognized as dangerous, although different from pack ice in terms of the peril they presented to the sailing ships. Icebergs were perceived as a lesser threat than pack ice to the sailing ships. Icebergs could be large and plentiful - but they still were only discrete obstacles, which could be avoided and sailed among with little difficulty and small delay. Pack ice, however, was frequently continuous and a barrier which could trap a ship or prevent its sailing. For these reasons, perhaps the log-book descriptions of icebergs are not as informative as those of pack ice.

8.1 Iceberg Notation used in the Log-books

Icebergs were described as *Isles of Ice* in the log-books for the 83 years of record from 1751 to 1833. The only exception occurred in 1821, when the log-keeper referred to an iceberg as an *Island of Ice*. In 1833 the officer who kept the log-book used both of the terms *Isles of Ice* and *Ice Berghs* to denote icebergs. In the following years from 1834 to 1870 the crews used the more modern term *iceberg* (berg is the German word for mountain), although occasionally it was spelled *Ice bergh*. Today the term ice island is used quite differently from its historical usage since it is applied to massive fragments of ice shelves drifting in the polar seas.

The presence and the relative number of icebergs was frequently recorded although the actual number present was often impossible to ascertain exactly. Icebergs were sighted in 110 or 94% of the 117 years of record, and there were 546 iceberg descriptions (an average of 4.7 comments per year) written in the log-books while the ships were in the Labrador Sea. The spatial distribution of these comments is presented in Figure 8.1. The number of comments per year ranged from zero to a high of 21 comments in 1832. The 546 iceberg comments were spread over 322 days, termed iceberg days, and the spatial distribution of iceberg days is plotted in Figure 8.2. The number of iceberg days ranged from zero to nine iceberg days in 1832. The numbers of iceberg comments and iceberg days are listed by year in Appendix 3.

The comments were almost never descriptive of the icebergs themselves, and usually dealt with the number of icebergs. A exceptionally detailed example was recorded by the crew of the Eddystone: "A large Isle of Ice 2 miles long" (HBCA, PAM, Eddystone log-book, July 16, 1812, C.1/296). Another unusual example occurred in 1834 when the log-keeper gave an aesthetic description of the scene: "Bergs in all directions presenting a very splendid sight" (HBCA, PAM, Prince George log-book, July 28, 1834, C.1/735). The most common adjectives used in these descriptions were *large* or *small*, as in the following example: "A large Isle of Ice to the NW off us" (HBCA, PAM, Prince of Wales I log-book, July 18, 1823, C.1/800), but even these terse adjectives are few and far between.

The most frequent form of comment only acknowledged the presence of icebergs in some quantity. There were two basic forms of quantification used in the log-books. The first was when the exact number of icebergs in sight was given, and the second was a subjective estimate such as *several* or *many*. Table 8.1 gives a frequency analysis of the occurrence of every quantitative term used in the 546 iceberg comments. Over half of the comments gave the exact number of icebergs seen. The most frequent sighting was of a single iceberg. Most comments which gave the actual number of icebergs referred to small quantities

Figure 8.1: Distribution of Iceberg Comments - All Years

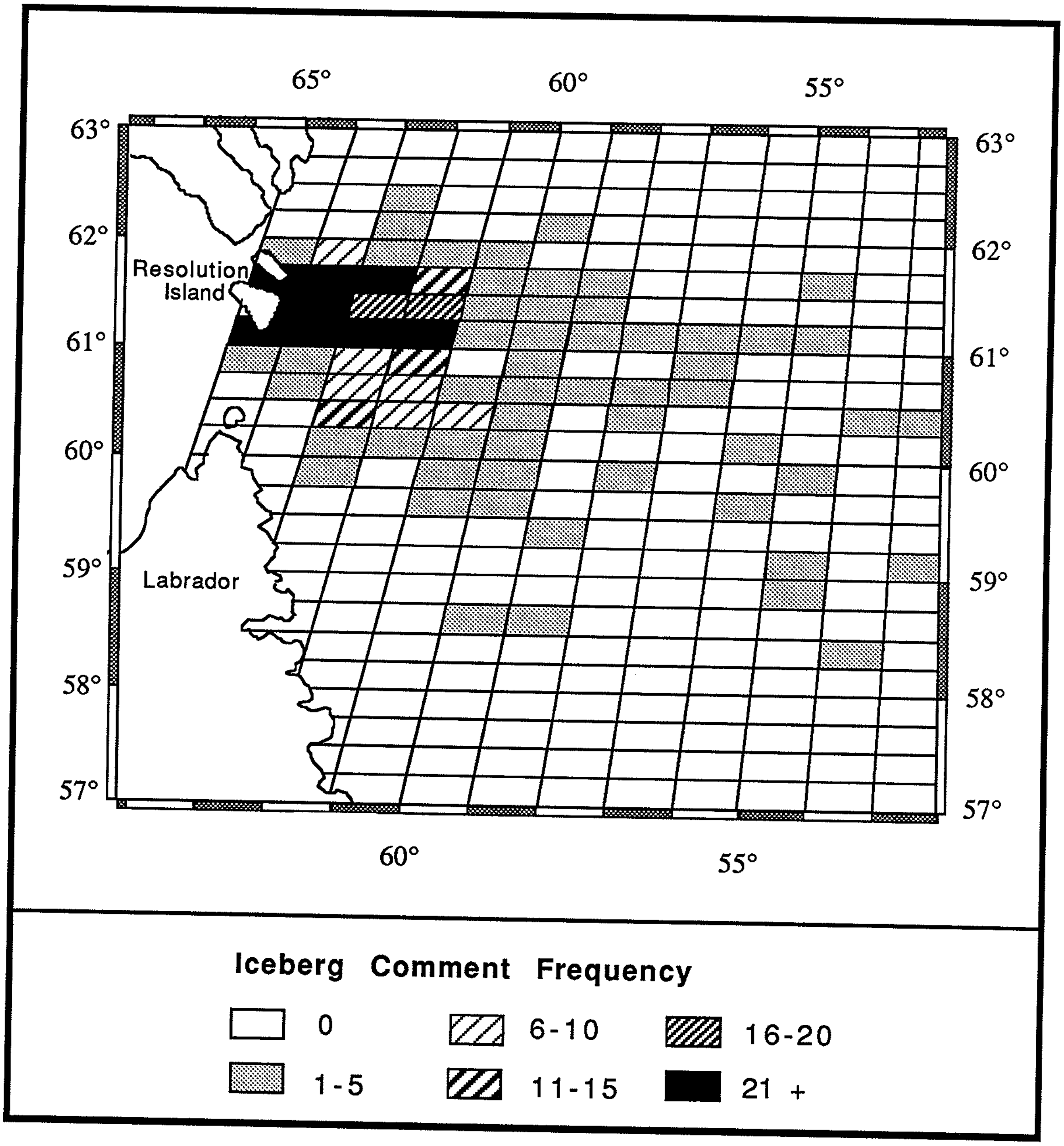


Figure 8.2: Distribution of Iceberg Days - All Years

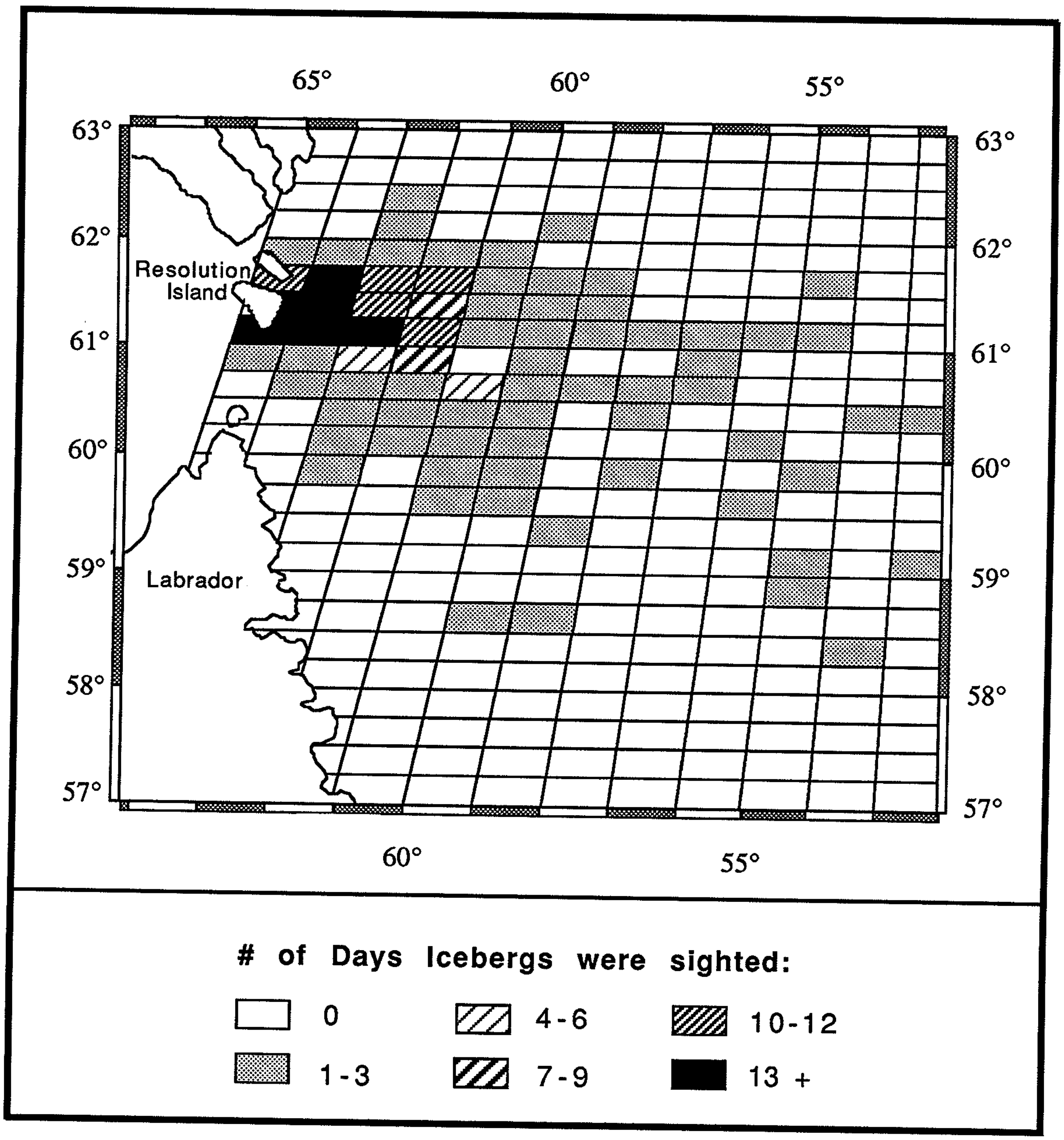


Table 8.1: Frequency Analysis of Descriptions used by HBC Crews to Quantify Icebergs

Frequency	Description of Quantity
305	(exact number 1 to 60; breakdown below)
175	several
12	many
12	a number of
9	some
8	a great many
8	Icebergs/ Isles of Ice
5	a great number
3	a quantity of
2	numerous
1	a few; amazing quantity of immeasurable; in sight all round in all directions; in great plenty

Frequency of Occurrence of Exact Numbers of Icebergs

Freq	Number	Freq	Number	Freq	Number
201	1	1	11	3	30
43	2	1	13	1	37
17	3	1	14	2	40
13	4	1	15	1	45
3	5	1	16	1	49
2	6	2	17	1	56
3	7	2	20	1	60
2	10	1	25		

of four or fewer. Only 4% of the total 546 iceberg comments comprised counts of more than seven icebergs.

8.2 Annual Estimate of Icebergs

The ships' officers who counted the number of icebergs, when there were more than six, did so more than once per voyage, therefore the 22 exact descriptions of more than seven icebergs are concentrated into a few years. These were years with mild pack ice or calm conditions so that the officers had sufficient leisure time to count up to 60 icebergs. A typical example is: "Thirty seven Isles of Ice in sight" (HBCA, PAM, Prince Rupert I log-book, July 27, 1757, C.1/874). When there were several icebergs in sight the officers often used inexact and subjective terms to quantify their frequencies. The most common of these inexact quantitative terms was *several* which was used in 73% of the subjective terms. The word *several* was used nearly fifteen times more often than the next most common subjective terms *many* and *a number of*. The list in Table 8.1 shows that some of these quantitative terms were indicative of large numbers but impossible to translate into exact numbers. An example is: "At 6 immeasurable Icebergs around the horizon" (HBCA, PAM, Prince George log-book, July 27, 1834, C.1/735).

Although 56% of the iceberg comments gave a precise number, the total number of icebergs sighted on an entire voyage can only be established in 35 years, which is less than 30% of the total. These 35 years include the seven years in which the crews observed no icebergs during the entire voyage. It is apparent that the years in which the total number of icebergs sighted is known were also years in which few icebergs were sighted. Thus in 30 out of 35 of these years five or fewer icebergs were reported by the crews, and in 34 of the 35 years, ten icebergs or fewer were observed.

To establish an annual estimate of the numbers of icebergs observed in the remaining 82 years a method of determining the value of the subjective terms was derived. An analysis of the subjective terms yielded two general groups. The first group contained terms which were interpreted as representing only a small number of icebergs, probably exceeding three. These terms are *a few*, *some*, and *Isles of Ice/ Icebergs*. This group represents only 7.5% of the subjective terms. The second group contained the remaining 92.5% of the subjective terms. The terms in this second group referred to a large number of icebergs having no determinable upper limit. Because of the uncertainty involved in dealing with these subjective terms, not even approximate values can be assigned to them. As a result, the 82 years in which subjective terms were used were broken into three groups. There were 23 years assigned to the first group **F** which contained descriptions indicating there were few icebergs sighted that year. Forty-two years were assigned to the second group **M** which had descriptions indicating a moderate to large number of iceberg sightings. The third group included the 17 years which had both subjective terms and exact numbers. In these years, by adding the numbers, it was possible to establish the minimum number of icebergs sighted. This was the minimum number observed since no values could be assigned to the subjective terms. These years were denoted by the number of icebergs sighted followed by +. The + was used to denote that the value was a conservative estimate of the number of icebergs sighted that year. An example of this third group occurred during the 1832 voyage of the Prince Rupert IV. In two days the crew counted more than 140 icebergs, and during the voyage there were 10 numeric descriptions which added up to 149 icebergs. The value of 149 is a particularly conservative estimate of the number of icebergs sighted in that year, however, since there were also 11 subjective descriptions describing *several* or *a great number* of icebergs spread over the nine iceberg days. The estimate of the number of icebergs sighted for each year is listed in Table 8.2 as well as in the data summary in Appendix 3.

Table 8.2: Annual Estimate of Icebergs: 1751-1870

Year	0	1	2	3	4	5	6	7	8	9
1750		0	23	9	M	F	1	40+	F	5
1760	51+	F	M	22+	19+	6	0	2	F	3
1770	2	M	2	F	M	M	10	1	35+	M
1780	M	5	0	35+	M	1	3	2	58+	M
1790	45+	M	35+	M	1	0	3	M	M	M
1800	3	15+	M	M	3	F	M	M	32+	M
1810	F	2	M	F	F	4	F	F	M	M
1820	2	1	F	3	M	M	F	7	F	F
1830	M	34+	149+	*M	M	M	M	M	17+	*
1840	*	*	0	M	3	F	F	F	0	M
1850	M	F	F	M	1	F	F	M	M	M
1860	4	M	M	18+	M	M	M	16+	90+	F
1870	0									

* no log-book for that year
\+ value is a conservative estimate
M many icebergs sighted that year
F few icebergs sighted that year

Chapter 9: Summary and Conclusion

Detailed interpretations and discussions of the Labrador Sea ice severity index were presented in Chapter 6 and Chapter 7 and the main purpose of this chapter is to provide a summary of the thesis and to add some concluding remarks. Although there are other sources available*, the HBC log-books probably provide the best source of historical sea ice information in the western portion of the Labrador Sea, and three properties of the log-books support this assertion. The ships followed the same general route across the Labrador Sea year after year, the log-books were kept in a uniform manner throughout the 120 year period, and the ships sailed through the Labrador Sea at roughly the same time of year. The ships left the Labrador Sea and entered Hudson Strait July 28 on average with a standard deviation of only 10 days. As a result, the log-books provide evidence of summer ice dispersal in the western portion of the Labrador Sea.

An uncertainty that was more acute in this study than in Faurer's (1981) analysis of Hudson Strait or in Catchpole and Halpin's (1987) analysis of eastern Hudson Bay, concerned the accuracy of the locations given by the coordinates in the log-books. In Faurer's study of Hudson Strait the ships were often within sight of landmarks which the officers used to pilot their ships. After their Atlantic crossing, however, the ships had been out of the sight of land for 30 days on average when the crews first saw Resolution Island. The technology was not available in the eighteenth century to permit the accurate determination of longitude at sea and, therefore, a method of testing navigational accuracy was devised. The general finding was that the mean error in the recorded longitudes was 8 nautical miles. Methods were developed to correct errors after the first sighting of Resolution Island and to locate the ships within a grid of rectangles with dimensions of 1° longitude by 15' latitude.

The method used by Faurer (1981), in which sea ice severity was inferred from voyage durations, was not applicable in this study because there was not a strong relationship between sea ice severity and the duration of the passage across the Labrador Sea. The methodology employed in this study was an adaptation of the method used by Catchpole and Halpin (1987) to derive the ice severity index in eastern Hudson Bay. An initial content analysis of the 895 individual ice descriptions transcribed from the log-books classified 45 separate word roots and phrases used to describe ice. The sea ice conditions of 1965 were used as a benchmark against which historic ice conditions were compared.

The ISI provides evidence of year-to-year variations in sea ice in the eastern approach to Resolution Island, and ranks the years with respect to their sea ice severity. The ice conditions in the 120 year period ranged from milder than present day mild conditions to more severe than present day extremes. There are no means whereby the ISI values can be calibrated against modern sea ice observations in the Labrador Sea. Consequently, the ISI must be treated as ordinal, not interval data. They permit us to rank the years according to ice severity, but they do not provide numerical measures of the amounts of ice in individual years.

Comparisons of the ranking obtained from the ISI with ice indices from Hudson Strait, eastern Hudson Bay, and western Hudson Bay, revealed that the ice severity in the Labrador Sea was not significantly correlated with the ice severity in these other seas. This finding was attributed to the important role played by atmospheric circulation in the summer dispersal of ice, and to the regional differences in this role among straits and bays varying in their orientations, dimensions, and water movements. A comparison of the ISI with other historic sea ice information for the Labrador Sea, compiled by Newell (1980, 1983), indicates similarities in the findings. However, caution must be used when discussing different parts of the Labrador Sea because of the complex interplay between the Baffin Current, the Hudson Strait Current, the Labrador Current and the West

Greenland Current in the study area. Different clearing patterns in years with early and late ice retreat, and the influence of ice from Hudson Strait make ice data from the Labrador coast difficult to compare with the ISI. Crane's (1978) analysis of ice clearing in the Labrador Sea is probably the most detailed available, and it was based on only 11 years of data. In the absence of a more detailed analysis of ice clearing in the Labrador Sea, it is difficult to fully utilize the information provided by the HBC log-books and Moravian mission data. Should a detailed analysis be undertaken, the HBC log-book data analysed with other historic sources would provide an even more informative sea ice history.

The period of study of this research, 1751 to 1870, covers several major eruptions. These include the 1835 eruption of Coseguina, which was assigned the highest DVI by Lamb (1970), and the eruption of Tambora in 1815, which was assigned the highest VEI of all eruptions that Newhall and Self (1980) ranked. The presence of a volcanic signal in the ISI was tested by an adaptation of superposed epoch analysis. The eruption years to be studied were selected using Lamb's DVI and Newhall and Self's VEI. The analysis yielded a highly significant volcanic signal in the year immediately following an eruption. The probability of a signal of this strength occurring by chance in the data is less than 0.0003. Two case studies of the post eruption years 1816 and 1836 revealed that ice conditions were more severe than present day extremes in the Labrador Sea and were exceptionally severe for the historical period. Both 1816 and 1836 were years of exceptionally cold and severe weather throughout Europe and North America.

It is suggested that any relationship between volcanic dust and sea ice severity involves the atmospheric circulation associated with dust veils. Crane (1978) found a relationship between the patterns of sea ice retreat and the relative displacement of the 700 millibar trough over Baffin Island. The results of this study together with Crane's findings suggest that there is a relationship between atmospheric circulation and dust veils. Possibly in the year following a large volcanic eruption there is a displacement of the 700 millibar trough to the east of its normal position. The eastward displacement of the trough results in less frequent occurrence of lows over northern Quebec and Foxe basin, which in turn results in the lower frequence of warm southerly airflow. The lower temperatures mean a slower rate of ablation and the reduced pressure gradient results in weaker winds and slower ice removal.

In addition to the analysis of pack ice, a brief examination of icebergs was made. Quantification proved to be very difficult since the numbers of icebergs sighted were often given using subjective estimates. The exact number of icebergs sighted could only be established in only 35 years. In 17 years the minimum number of icebergs sighted could be determined, thus providing a conservative estimate. In the remaining 65 years a numeric value could not be assigned and it could only be determined if few or many icebergs were sighted.

REFERENCES A: PRIMARY SOURCES

All historical documents are from the Hudson's Bay Company Archives (HBCA) in the Provincial Archives of Manitoba.

Hudson's Bay Company Ships' Log-books

YEAR	SHIP'S NAME	HBCA PIECE #	Microfilm REEL #
1751	King George I	C.1/360	2M32
1752	King George I	C.1/361	2M32/2M33
1753	King George I	C.1/362	2M33
1754	King George I	C.1/363	2M33
1755	King George I	C.1/364	2M33
1756	Prince Rupert II	C.1/878	2M90
1757	Prince Rupert I	C.1/874	2M90
1758	Prince Rupert II	C.1/880	2M91
1759	Prince Rupert II	C.1/881	2M91
1760	Prince Rupert II	C.1/882	2M91
1761	King George II	C.1/365	2M33
1762	King George II	C.1/366	2M33
1763	King George II	C.1/367	2M33
1764	King George II	C.1/368	2M33
1765	King George II	C.1/369	2M34
1766	King George II	C.1/370	2M34
1767	King George II	C.1/371	2M34
1768	King George II	C.1/372	2M34
1769	King George II	C.1/373	2M34
1770	King George II	C.1/374	2M34
1771	King George II	C.1/375	2M34
1772	Prince Rupert III	C.1/895	2M93
1773	King George II	C.1/377	2M35
1774	Prince Rupert III	C.1/897	2M93
1775	Prince Rupert III	C.1/898	2M93/2M94
1776	King George II	C.1/380	2M35
1777	Prince Rupert III	C.1/900	2M94
1778	Prince Rupert III	C.1/901	2M94
1779	King George III	C.1/383	2M36
1780	King George III	C.1/384	2M36
1781	King George III	C.1/385	2M36
1782	King George III	C.1/386	2M36
1783	Prince Rupert	C.1/905	2M95
1784	King George III	C.1/387	2M36
1785	King George III	C.1/388	2M37
1786	King George III	C.1/389	2M37
1787	King George III	C.1/390	2M37
1788	King George III	C.1/391	2M37
1789	King George III	C.1/392	2M37
1790	Seahorse	c.1/1053	2M125

YEAR	SHIP'S NAME	HBCA PIECE #	Microfilm REEL #
1791	King George III	C.1/393	2M37/2M38
1792	King George III	C.1/394	2M38
1793	King George III	C.1/395	2M38
1794	Prince of Wales I	C.1/738	2M67
1795	Prince of Wales I	C.1/740	2M67
	King George III	C.1/398	2M67
1796	Prince of Wales I	C.1/741	2M67
1797	Prince of Wales I	C.1/744	2M68
1798	Prince of Wales I	C.1/745	2M68
1799	Prince of Wales I	C.1/747	2M68
1800	Prince of Wales I	C.1/749	2M68
1801	King George III	C.1/410	2M40
1802	Prince of Wales I	C.1/754	2M70
1803	Prince of Wales I	C.1/756	2M70
1804	Prince of Wales I	C.1/759	2M70
1805	Prince of Wales I	C.1/762	2M71
1806	Prince of Wales I	C.1/766	2M72
1807	Prince of Wales I	C.1/769	2M72
1808	Prince of Wales I	C.1/771	2M73
1809	Prince of Wales I	C.1/772	2M73
1810	Prince of Wales I	C.1/774	2M73
		C.1/775	2M73
		C.1/776	2M74
1811	Prince of Wales I	C.1/777	2M74
1812	Eddystone	C.1/296	2M22
1813	Prince of Wales I	C.1/779	2M74
1814	Prince of Wales I	C.1/781	2M74
1815	Prince of Wales I	C.1/783	2M75
1816	Prince of Wales I	C.1/785	2M75
1817	Eddystone	C.1/305	2M24
1818	Prince of Wales I	C.1/787	2M75
	Eddystone	C.1/306	2M24
1819	Prince of Wales I	C.1/789	2M76
1820	Prince of Wales I	C.1/792	2M76
1821	Prince of Wales I	C.1/796	2M77
1822	Prince of Wales I	C.1/797	2M77
1823	Prince of Wales I	C.1/800	2M78
1824	Prince of Wales I	C.1/803	2M78
1825	Prince of Wales I	C.1/807	2M79
1826	Prince of Wales I	C.1/809	2M79
		C.1/810	2M79
1827	Prince of Wales I	C.1/813	2M80
1828	Prince of Wales I	C.1/815	2M80
		C.1/817	2M80
1829	Prince of Wales I	C.1/819	2M81
1830	Prince of Wales I	C.1/821	2M81
1831	Prince Rupert IV	C.1/922	2M98
1832	Prince Rupert IV	C.1/924	2M98
1833	Prince of Wales I	C.1/825	2M82

YEAR	SHIP'S NAME	HBCA PIECE #	Microfilm REEL #
1834	Prince George	C.1/735	2M66
1835	Prince of Wales I	C.1/827	2M82
1836	Prince of Wales I	C.1/830	2M83
		C.1/831	2M83
	Prince Rupert IV	C.1/930	2M99
1837	Prince Rupert IV	C.1/931	2M99
		C.1/932	2M100
1838	Prince Rupert IV	C.1/933	2M100
1842	Prince Rupert V	C.1/934	2M100
		C.1/935	2M100
1843	Prince Rupert V	C.1/938	2M101
1844	Prince Rupert V	C.1/942	2M101
1845	Prince Albert	C.1/677	2M57
1846	Prince Albert	C.1/679	2M57
1847	Prince Albert	C.1/680	2M57
1848	Prince Albert	C.1/683	2M58
		C.1/684	2M58
1849	Prince Albert	C.1/686	2M58
1850	Prince Rupert V	C.1/963	2M105
1851	Prince Albert	C.1/692	2M59
1852	Prince Albert	C.1/697	2M60
1853	Prince Albert	C.1/699	2M60
1854	Prince Arthur	C.1/705	2M61
1855	Prince Arthur	C.1/708	2M62
1856	Prince Arthur	C.1/710	2M62
1857	Prince Arthur	C.1/713	2M63
1858	Prince Arthur	C.1/716	2M63
1859	Prince Arthur	C.1/719	2M64
1860	Prince Arthur	C.1/722	2M64
1861	Prince Arthur	C.1/725	2M65
1862	Prince Arthur	C.1/727	2M65
1863	Prince Arthur	C.1/729	2M65
1864	Prince Arthur	C.1/734	2M66
1865	Prince Rupert VI	C.1/965	2M105
1866	Prince Rupert VI	C.1/968	2M105
1867	Prince Rupert VI	C.1/970	2M106
1868	Prince Rupert VI	C.1/971	2M106
1869	Prince Rupert VI	C.1/973	2M106
1870	Ladyhead	C.1/442	2M45

Hudson's Bay Company Post Journals

YEAR	POST	HBCA PIECE #
1816	Fort George	B77/a/3
1816	Eastmain	B77/a/3
1816	Naosquiscaw	B143/a/15
1816	New Brunswick	B145/a/34

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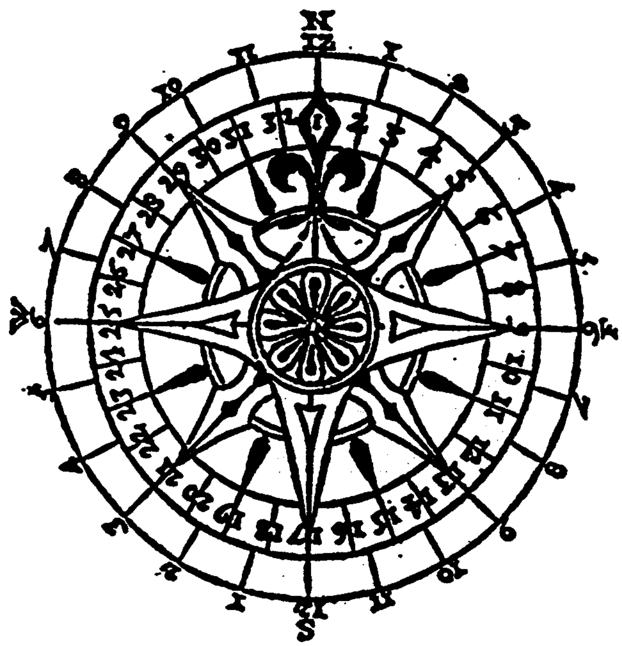
APPENDIX 1: THE 32 POINT COMPASS

The 32-Point Compass:



(1 point = 11¼ degrees)

Names of compass points (by number):

1. N	9. E	17. S	25. W
2. N&byE	10. E&byS	18. S&byW	26. W&byN
3. NNE	11. ESE	19. SSW	27. WNW
4. NE&byN	12. SE&byE	20. SW&byS	28. NW&bW
5. NE	13. SE	21. SW	29. NW
6. NE&byE	14. SE&bS	22. SW&byW	30. NW&byN
7. ENE	15. SSE	23. WSW	31. NNW
8. E&byN	16. S&byE	24. W&byS	32. N&byW

(adapted from Faurer, 1981)

APPENDIX 2

Glossary of Sailing Manoeuvres*

BRING TO: To check the course of the ship, by arranging the sails in such a manner as that they shall counteract each other, and keep her nearly stationary.

GRAPPLE: A sort of small anchor fitted with four or five flooks or claws. Used in the Labrador sea and other northern waters to fasten the ship to a large piece of ice.

HAULED UP: (Hall'd up) similar to bring to.

STANDING OFF: When speaking of a vessel, is to keep at a competent distance, so as to be clear of danger.

STANDING ON: Is to continue the course on which a ship sails.

STANDING OFF AND ON: Is to keep alternatively near to the ice and clear of it.

TACKING: Is a manoeuvre of crossing the ship's bow across the wind. It requires a disciplined crew and good timing. At the command 'Helm's Alee', the helm is put down, pointing the ship directly into the wind, while the yards are quickly braced around to catch the wind from the other direction.

WEARING: Is another manoeuvre of crossing the wind, by passing the ship's stern across the wind. It is a slower method than tacking, and the ship ends up far downwind from where it started.

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* Definitions are adapted from W. Falconer's *New Universal Dictionary of the Marine* and J. Williams' *Heart of Oak.*

Appendix 3: Summary of Data for all Years

#	YEAR	PD	Dates DD	DES	DAC	Comments 0	1	2	3	4	Days 1	2	3	4	ISI	Icebergs IBC	IBD	IBI
1	1751	O	10	36	26	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1752	O	6	37	31	0	1	1	3	0	1	1	2	0	30	6	4	23
3	1753	O	22	58	36	0	6	8	4	19	1	2	2	10	192	4	3	9
4	1754	O	20	42	22	0	2	5	0	0	1	3	0	0	20	4	3	M
5	1755	O	23	54	31	0	3	0	0	0	2	0	0	0	6	3	2	F
6	1756	O	19	43	24	0	1	0	0	0	1	0	0	0	2	1	1	1
7	1757	O	19	57	38	0	0	0	0	0	0	0	0	0	0	4	2	40+
8	1758	O	24	48	24	0	0	0	0	0	0	0	0	0	0	1	1	F
9	1759	O	24	57	33	1	2	1	1	0	0	0	1	0	12	5	4	5
10	1760	O	25	59	34	0	1	3	0	0	0	3	0	0	22	8	4	51+
11	1761	O	25	59	34	0	2	0	0	0	2	0	0	0	8	2	1	F
12	1762	O	37	58	21	0	5	2	0	0	2	2	0	0	28	5	3	M
13	1763	O	30	58	28	0	2	2	0	0	2	1	0	0	26	6	3	22+
14	1764	O	27	57	30	1	1	0	0	0	1	0	0	0	4	5	5	19+
15	1765	K	17	65	48	0	1	2	5	0	0	0	4	0	44	4	3	6
16	1766	K	24	53	29	0	1	0	0	0	1	0	0	0	3	0	0	0
17	1767	K	27	63	36	0	3	3	4	2	1	1	1	2	44	1	1	2
18	1768	O	24	53	29	0	1	0	0	0	1	0	0	0	5	3	3	F
19	1769	O	25	62	37	0	0	0	0	0	0	0	0	0	0	3	3	3
20	1770	O	26	59	33	0	0	6	0	0	0	2	0	0	16	2	2	2
21	1771	O	25	58	33	0	0	0	0	0	0	0	0	0	0	2	2	M
22	1772	O	27	60	33	0	0	1	0	0	0	1	0	0	8	3	2	2
23	1773	O	26	62	36	0	1	2	0	0	1	1	0	0	13	2	1	F
24	1774	O	25	52	27	0	2	0	0	0	2	0	0	0	9	3	2	M
25	1775	O	27	55	28	0	4	2	0	0	2	1	0	0	18	5	5	M
26	1776	O	33	68	35	1	1	3	1	0	1	3	1	0	42	6	5	10

			Dates			Comments					Days					Icebergs		
#	YEAR	PD	DD	DES	DAC	0	1	2	3	4	1	2	3	4	ISI	IBC	IBD	IBI
27	1777	O	25	57	32	0	0	0	0	0	0	0	0	0	0	1	1	1
28	1778	O	25	55	30	1	6	2	1	0	2	1	1	0	12	8	4	35+
29	1779	O	36	73	37	0	0	0	0	0	0	0	0	0	0	8	5	M
30	1780	O	29	73	44	0	0	1	1	0	0	0	1	0	15	5	3	M
31	1781	O	26	60	34	0	1	0	0	0	1	0	0	0	4	3	3	5
32	1782	O	36	62	26	0	0	0	0	0	0	0	0	0	0	0	0	0
33	1783	O	29	70	41	0	0	0	0	0	0	0	0	0	0	13	5	35+
34	1784	O	33	75	42	0	1	0	0	0	1	0	0	0	5	9	7	M
35	1785	O	29	65	36	0	0	0	0	0	0	0	0	0	0	1	1	1
36	1786	O	25	60	35	0	2	0	0	0	1	0	0	0	4	2	2	3
37	1787	O	22	50	28	0	0	0	0	0	0	0	0	0	0	2	2	2
38	1788	O	24	54	30	0	3	5	1	0	2	1	1	0	28	5	4	58+
39	1789	O	23	44	21	0	0	0	0	0	0	0	0	0	0	4	2	M
40	1790	O	29	63	34	0	3	4	1	0	1	3	1	0	41	2	2	45+
41	1791	O	40	73	33	0	5	2	0	0	2	1	0	0	23	6	5	M
42	1792	O	23	55	32	0	3	4	0	0	1	3	0	0	25	6	3	35+
43	1793	O	25	48	23	0	3	4	1	0	0	1	1	0	17	2	1	M
44	1794	O	28	61	33	0	3	0	0	0	1	0	0	0	4	1	1	1
45	1795	O	33	68	35	0	0	0	0	0	0	0	0	0	0	0	0	0
46	1796	O	28	56	28	0	0	0	0	0	0	0	0	0	0	3	1	3
47	1797	O	36	56	20	0	7	0	0	0	3	0	0	0	13	6	2	M
48	1798	O	34	73	39	1	3	1	0	0	1	1	0	0	21	6	5	M
49	1799	O	37	66	29	0	1	4	0	1	1	3	0	1	48	3	2	M
50	1800	O	36	80	44	0	1	1	0	0	1	1	0	0	18	3	2	3
51	1801	O	13	51	38	0	3	5	0	0	2	3	0	0	20	10	8	15+
52	1802	O	25	57	32	0	2	2	0	0	0	1	0	0	8	7	4	M
53	1803	O	27	55	28	0	1	0	0	0	1	0	0	0	3	5	4	M
54	1804	O	27	46	19	0	1	4	2	0	0	1	2	0	24	2	1	3

#	YEAR	PD	Dates DD	DES	DAC	Comments 0	1	2	3	4	Days 1	2	3	4	ISI	Icebergs IBC	IBD	IBI
55	1805	O	33	63	30	0	4	2	0	0	1	2	0	0	20	3	3	F
56	1806	O	28	55	27	0	4	2	0	0	0	2	0	0	12	4	1	M
57	1807	O	36	79	43	0	3	1	0	0	1	1	0	0	18	6	4	M
58	1808	O	13	44	31	0	3	5	0	0	2	2	0	0	19	10	4	32+
59	1809	O	28	61	33	0	0	3	1	0	0	1	2	0	27	5	3	M
60	1810	S	29	46	17	1	2	5	0	0	0	3	0	0	18	2	2	F
61	1811	S	56	98	42	0	0	0	0	0	0	0	0	0	0	2	2	2
62	1812	O	23	49	26	0	7	6	5	0	1	1	4	0	43	9	5	M
63	1813	O	28	59	31	0	2	0	0	0	2	0	0	0	5	1	1	F
64	1814	O	29	58	29	0	0	0	0	0	0	0	0	0	0	2	1	F
65	1815	O	25	55	30	0	0	0	0	0	0	0	0	0	0	3	3	4
66	1816	O	11	65	54	0	16	41	19	41	2	3	2	21	310	2	2	F
67	1817	O	3	23	20	0	1	9	0	0	1	5	0	0	12	3	2	F
68	1818	O	15	44	29	0	4	6	0	0	0	2	0	0	8	5	4	M
69	1819	O	16	68	52	1	5	3	0	0	1	3	0	0	17	5	4	M
70	1820	O	21	53	32	0	3	1	0	0	1	1	0	0	11	2	2	2
71	1821	O	17	41	24	0	1	2	0	1	0	1	0	1	4	1	1	1
72	1822	O	24	53	29	0	7	7	2	1	0	1	1	1	30	2	2	F
73	1823	O	19	55	36	0	2	10	4	11	0	3	1	4	77	2	2	3
74	1824	O	29	51	22	0	5	0	0	0	3	0	0	0	9	10	4	M
75	1825	O	23	51	28	0	1	2	0	0	1	1	0	0	10	4	2	M
76	1826	O	44	84	40	0	1	0	0	0	1	0	0	0	6	3	2	F
77	1827	O	19	48	29	2	13	5	0	0	2	3	0	0	18	3	2	7
78	1828	O	25	51	26	1	5	2	0	1	2	1	0	1	24	3	2	F
79	1829	O	29	49	20	0	5	0	2	1	1	0	0	1	15	2	1	F
80	1830	O	31	59	28	0	3	5	0	0	0	2	0	0	18	10	5	M
81	1831	O	32	69	37	0	8	0	0	0	6	0	0	0	30	18	8	34+
82	1832	S	25	68	43	1	8	35	14	10	1	2	5	7	186	21	9	149+
83	1833	O	27	54	27	0	13	6	1	2	1	4	1	2	71	6	2	M
84	1834	O	23	59	36	0	5	9	0	3	0	2	0	2	50	5	3	M

#	YEAR	PD	Dates			Comments					Days					Icebergs		
			DD	DES	DAC	0	1	2	3	4	1	2	3	4	ISI	IBC	IBD	IBI
85	1835	O	25	58	33	0	10	5	0	0	3	3	0	0	31	9	6	M
86	1836	O	23	62	39	0	7	7	3	7	0	2	0	4	82	5	5	M
87	1837	S	24	49	25	1	0	0	0	0	0	0	0	0	0	6	2	M
88	1838	O	24	56	32	0	3	4	1	0	1	2	1	0	33	12	5	17+
	1839	*No Data Available*																
	1840	*No Data Available*																
	1841	*No Data Available*																
89	1842	O	28	60	32	0	6	12	0	0	1	6	0	0	46	0	0	0
90	1843	O	25	51	26	0	2	1	0	0	1	1	0	0	13	6	2	M
91	1844	O	25	48	23	2	8	8	0	0	1	4	0	0	23	3	2	3
92	1845	O	26	52	26	0	5	3	0	0	1	2	0	0	17	2	2	F
93	1846	O	21	46	25	0	2	3	0	0	1	2	0	0	12	2	2	F
94	1847	O	24	55	31	0	2	5	0	0	1	3	0	0	24	1	1	F
95	1848	S	25	45	20	0	5	9	1	1	0	1	1	1	22	0	0	0
96	1849	S	27	58	31	0	0	0	0	0	0	0	0	0	0	6	3	M
97	1850	L	10	45	35	1	4	7	0	0	0	3	0	0	16	3	2	M
98	1851	O	32	56	24	0	2	2	0	0	0	1	0	0	8	2	1	F
99	1852	O	34	59	25	0	3	3	0	0	1	1	0	0	9	1	1	F
100	1853	O	34	66	32	0	0	1	0	0	0	1	0	0	0	3	3	M
101	1854	O	28	46	18	0	2	3	0	6	0	1	0	2	24	1	1	1
102	1855	O	35	61	26	0	10	6	0	4	0	1	0	3	56	1	1	F
103	1856	O	34	62	28	0	8	5	0	6	0	2	0	3	48	1	1	F
104	1857	L	22	55	33	0	2	1	0	0	1	2	0	0	20	3	2	M
105	1858	O	37	57	20	1	1	2	0	0	0	1	0	0	8	4	2	M
106	1859	O	31	62	31	0	4	2	0	0	1	1	0	0	12	4	2	M
107	1860	O	39	70	31	0	0	0	0	0	0	0	0	0	0	4	3	4
108	1861	O	36	68	32	0	3	0	0	0	3	0	0	0	11	6	3	M
109	1862	O	36	59	23	0	2	8	0	0	0	3	0	0	24	9	4	M
110	1863	O	32	68	36	0	5	8	0	0	0	3	0	0	35	21	7	18+
111	1864	O	32	64	32	0	0	0	0	0	0	0	0	0	0	7	4	M

#	YEAR	PD	Dates DD	DES	DAC	Comments 0	1	2	3	4	Days 1	2	3	4	ISI	Icebergs IBC	IBD	IBI
112	1865	O	37	62	25	0	2	4	0	1	0	1	0	1	24	8	5	M
113	1866	O	33	57	24	0	0	1	0	0	0	1	0	0	10	4	3	M
114	1867	O	33	58	25	0	1	1	0	0	1	1	0	0	12	6	3	16+
115	1868	O	33	68	35	0	0	0	0	0	0	0	0	0	0	19	5	90+
116	1869	O	33	63	30	0	0	0	0	0	0	0	0	0	0	5	5	F
117	1870	O	33	58	25	0	0	6	0	0	0	4	0	0	32	0	0	0
TOTAL			-	-	-	16	319	364	78	118	90	140	36	67	-	545	322	-
AVERAGE			27	58	31	-	-	-	-	-	-	-	-	-	22	4.7	2.8	-

<u>***Key To Headings:***</u>

PD Port of Departure. This was the last port in Britain before convoy began Atlantic crossing.
O - Orkney; S - Stornaway, Lewis K - Kinsale, Ireland; L - London.

Dates DD Date of Departure from PD (Chapter 2.2). May 31 = Day 0; June 1 = Day 1; June 2 = Day 2; etc.
DES Date of Entry into Hudson Strait (Chapter 2.2).
DAC Duration of Atlantic Crossing in Days; DAC=DES-DD; (Chapter 2.2).

Comments 0 to 4 Total comments for that voyage, coded using Figure 5.1.

Days 1 to 4 Daily ice severity indices, **s**, by code (Chapter 5).

ISI Ice Severity Index for the Labrador Sea (Chapter 5).

Icebergs IBC Total Iceberg Comments for year (Chapter 8).
IBD Total number of Days icebergs were sighted (Chapter 8).
IBI Iceberg index for Labrador Sea (Chapter 8): F=Few; M=Many; + indicates conservative estimate.