

# **Arctic Shipping in Canada: Analysis of Sea Ice, Shipping, and Vessel Track Reconstruction**

Larissa Anna Vincenza Pizzolato

A thesis submitted to the  
Faculty of Graduate and Postdoctoral Studies  
in partial fulfillment of the requirements for the degree of  
Master of Science in Physical Geography

**Department of Geography**

**Faculty of Arts**

**University of Ottawa**

*Supervisors:*

Dr. Jackie Dawson and Dr. Luke Copland

*Thesis Committee:*

Dr. Stephen Howell and Dr. Michael Sawada

## TABLE OF CONTENTS

<b>LIST OF TABLES .....</b>	<b>iv</b>
<b>LIST OF FIGURES .....</b>	<b>v</b>
<b>LIST OF ACRONYMS .....</b>	<b>vii</b>
<b>ABSTRACT.....</b>	<b>viii</b>
<b>ACKNOWLEDGEMENTS .....</b>	<b>ix</b>
<b>CHAPTER 1: Introduction.....</b>	<b>1</b>
1.1 Study Area.....	2
1.2 Sea Ice of the Canadian Arctic .....	4
1.3 Shipping in the Canadian Arctic.....	6
1.4 Interactions between Sea Ice and Shipping Activity.....	11
1.5 Research Objectives and Organization of Thesis.....	11
1.6 Authorship and Co-author Contributions .....	13
<b>CHAPTER 2: Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012 .....</b>	<b>14</b>
2.1 Abstract .....	14
2.2 Introduction .....	15
2.3 Data Description.....	18
2.3.1 Vessel (NORDREG) Dataset .....	18
2.3.2 Sea Ice Dataset.....	21
2.3.3 Ancillary Datasets .....	22
2.4 Analytical Methodologies .....	23
2.5 Results .....	24
2.5.1 Shipping Trends and Variability .....	24
2.5.2 Sea Ice Trends and Variability.....	28
2.5.3 Relationships between Arctic Shipping, Sea Ice and the Atmosphere .....	31
2.6 Conclusions .....	35
<b>CHAPTER 3: Generation of Arctic Shipping Routes in Canada using a Least Cost Path Approach: Case Study for 2010.....</b>	<b>38</b>
3.1 Abstract .....	38

3.2	Introduction .....	39
3.3	Study Area .....	42
3.4	Data Description .....	42
	3.4.1 NORDREG Ship Archive .....	42
	3.4.2 AIS Ship Archive .....	43
	3.4.3 Canadian Ice Service Digital Archive (CISDA) .....	44
	3.4.4 Bathymetry .....	46
3.5	Case Study Selection .....	46
3.6	Least Cost Path Reconstruction Methodology .....	47
	3.6.1 Validation .....	57
3.7	Results .....	59
3.8	Discussion.....	64
3.9	Conclusions .....	65
	<b>CHAPTER 4: Conclusions.....</b>	<b>67</b>
4.1	Contributions .....	68
4.2	Limitations.....	70
4.3	Future Work.....	72
	<b>CHAPTER 5: References .....</b>	<b>74</b>

## LIST OF TABLES

Table 1.1. Description of different vessel types and their associated uses (compiled from Arctic Council, 2009, their Tables 5.2 and 8.1).....	8
Table 2.1. NORDREG Vessel Type Classifications grouped into 10 categories. ....	19
Table 2.2. Sen’s slope of decadal vessel count trends in the NORDREG zone, 1990 - 2012. <sup>a, b</sup> .	27
Table 2.3. Sen’s slope trends for mean monthly and shipping season (June 25 to October 15) sea ice area within the NORDREG zone, 1990 - 2012. <sup>a</sup> .....	30
Table 2.4. Kendall’s Tau Correlations for mean monthly sea ice area (km <sup>2</sup> year <sup>-1</sup> ) and monthly vessel counts in the NORDREG zone for July through October, 1990 - 2012. <sup>a, b</sup> .....	32
Table 3.1. Spatial resolution, accuracy, and data format of LCP analysis data sources. ....	49
Table 3.2. Least cost path cost surface reclassification. ....	53
Table 3.3. Error estimate for voyage track accuracy compared to AIS points, 2010. ....	59
Table 3.4. Summary of LCP statistics by vessel type for 2010. ....	60

## LIST OF FIGURES

Figure 1.1. Map of NORDREG zone study area outlining the two major Canadian Arctic shipping routes:the NWP northern route (N-NWP), the southern NWP route (S-NWP) and the Arctic Bridge (AB) (CCG, 2013; Howell and Yackel, 2004).....	3
Figure 2.1. Map of the NORDREG zone boundary and Arctic Shipping Routes, derived using the CISIRR, Canadian Coast Guard NORDREG zone, and AMSA Shipping Routes (CCG, 2013; Arctic Council,2009).....	16
Figure 2.2. Regime shifts were detected for all cut-off values in 2007; no regime shifts were detected in any other year for annual vessel counts, 1990-2012. Cut-off values represent the number of years used in regime detection window thresholds.....	25
Figure 2.3. Total monthly vessel counts from May through November in the NORDREG zone, 1990 – 2012.....	26
Figure 2.4. Time series of shipping season mean total ice, MYI, and FYI area (km <sup>2</sup> ) in the NORDREG zone, 1990 – 2012.....	29
Figure 2.5. Moving window Kendall’s Tau correlation analysis to measure the relationship between shipping season mean ice area (a. Total, b. MYI, c. FYI) and annual vessel counts in the NORDREG zone. Red markers denote significant correlations at the 95% confidence level or higher. Confidence intervals become increasingly larger as the time series shortens as we become less confident in the correlations due to the smaller sample size. ....	33
Figure 3.1. Map of NORDREG zone study area outlining the major Canadian Arctic shipping routes of the NWP northern route (N-NWP), southern NWP route (S-NWP), and the Arctic Bridge (AB) (CCG, 2013; Howell and Yackel, 2004).....	40
Figure 3.2. CISDA Weekly Regional Ice Chart Coverage over the NORDREG zone. ....	45
Figure 3.3. Least cost path workflow.....	48
Figure 3.4. Least cost path cost surface generation workflow.....	50
Figure 3.5. Point distance from coastline for all NORDREG records (Percentage of total records derived from n= 89 669) .....	52
Figure 3.6. (A) NORDREG ship archive points for one vessel voyage. (B) Weighted cost surface for a vessel with a maximum draft of 10 m, and for the ice chart dated October 11th, 2010 showing the associated LCP reconstructed segments. (C) Weighted cost surface for a vessel with a maximum draft of 10 m, and for the ice chart dated November 1st, 2010 showing the associated LCP reconstructed voyage segments. (D) Comparison of the LCP reconstructed vessel voyage segments to the known AIS points on the same date.....	56

Figure 3.7. LCP voyage tracks by vessel type in the NORDREG zone, 2010. .... 61

Figure 3.8. Bulk Carrier and Tanker Ship vessel tracks for (a) 2010, with a close-up of LCP predicted voyage tracks in (b) the central CAA and (c) Hudson Bay..... 62

Figure 3.9. Sum of total distance travelled (km) within each grid cell (25 km x 25 km) by vessel type, 2010..... 63

## LIST OF ACRONYMS

AB	Arctic Bridge
AIS	Automatic Identification System
AMSA	Arctic Marine Shipping Assessment
CAA	Canadian Arctic Archipelago
CCG	Canadian Coast Guard
CIS	Canadian Ice Service
CISIRR	Canadian Ice Service Ice Regime Regions
CISDA	Canadian Ice Service Digital Archive
DFO	Department of Fisheries and Oceans Canada
FYI	First-year Ice
HB	Hudson Bay
IMO	International Maritime Organization
LCP	Least Cost Path
MMSI	Marine Mobile Service Identity
MSL	Melt Season Length
MYI	Multi-year Ice
NORDREG	Vessel Traffic Services Reporting Zone Arctic Canada
NSR	Northern Sea Route
NWP	Northwest Passage
QEI	Queen Elizabeth Islands
SAT	Surface Air Temperatures
SIC	Sea Ice Concentration

## ABSTRACT

Declining sea ice area in the Canadian Arctic has gained significant attention with respect to the prospect of increased shipping activities along the Northwest Passage and Arctic Bridge shipping routes. Temporal trend and correlation analysis was performed on sea ice area data for total, first-year ice (FYI), and multi-year ice (MYI), and observed shipping activity within the Vessel Traffic Reporting Arctic Canada Traffic Zone (NORDREG zone) from 1990 to 2012. Relationships between declines in sea ice area and Arctic maritime activity were investigated alongside linkages to warming surface air temperatures (SAT) and an increasing melt season length. Statistically significant increases in vessel traffic were observed on monthly and annual time-scales, coincident with declines in sea ice area. Despite increasing trends, only weak correlations between the variables were identified, suggesting that other non-environmental factors have likely contributed to the observed increase in Arctic shipping activity including tourism demand, community re-supply needs, and resource exploration trends.

As a first step towards quantifying spatial variability in shipping patterns, a case study was conducted using 2010 observed shipping data to reconstruct historical shipping routes using a least cost path (LCP) approach. This approach was able to successfully reconstruct vessel tracks compared to an independent data source (Automatic Identification System) to an accuracy of  $10.42 \text{ km} \pm 0.67 \text{ km}$  over the entire study area. A 25 km gridded product across the entire Canadian Arctic domain was produced for 2010, with this approach now providing a basis to apply this method over the entire record (since 1990) in future studies to investigate long term spatial variability and change of shipping activity across the Canadian Arctic.

## ACKNOWLEDGEMENTS

This thesis would not have been possible without the funding support and guidance from my supervisors Dr. Jackie Dawson of the Environment Society and Policy Group (ESPG) and Dr. Luke Copland of the Laboratory of Cryospheric Research (LCR), and all of their support from the University of Ottawa, National Science and Engineering Research Council (NSERC) Discovery, Ontario Research Fund, the Social Sciences and Humanities Research Council (SSHRC), and the Canada Foundation for Innovation. I cannot thank them both enough for all of the amazing opportunities that I have been given thanks to their support! I would also like to acknowledge my committee members Dr. Stephen Howell and Dr. Mike Sawada for providing advice, support, and expertise throughout the completion of this thesis. I would also like to acknowledge the support of all of my colleagues at Environment Canada's Climate Research Division who were instrumental in the first section of this thesis (Drs. Chris Derksen and Stephen Howell, Peter Toose, and Mike Brady), and who introduced me to the exciting world that is Arctic science!

This research was also supported by the Ontario Graduate Scholarship, a NSERC Canada Graduate Scholarship (CGS), the Network of Expertise for Transportation in Arctic Waters (NEXTAW), Transport Canada, an NSERC Environment Canada Atmospheric and Meteorological Graduate Supplement, and the John W. Davies Memorial Award. Travel support for attending conferences and participating in field courses was generously provided by the Faculty of Graduate and Postdoctoral Studies at the University of Ottawa, CUPE2626, ArcticNet, GlacioEx, and the Northern Scientific Training Program who provided financial support for visiting the Coastguard facilities in Iqaluit. I would especially like to acknowledge

Environment Canada's Climate Research Division and the Canadian Ice Service, the staff at MCTS Iqaluit, and Transport Canada for providing the data, without which this thesis would not have been possible.

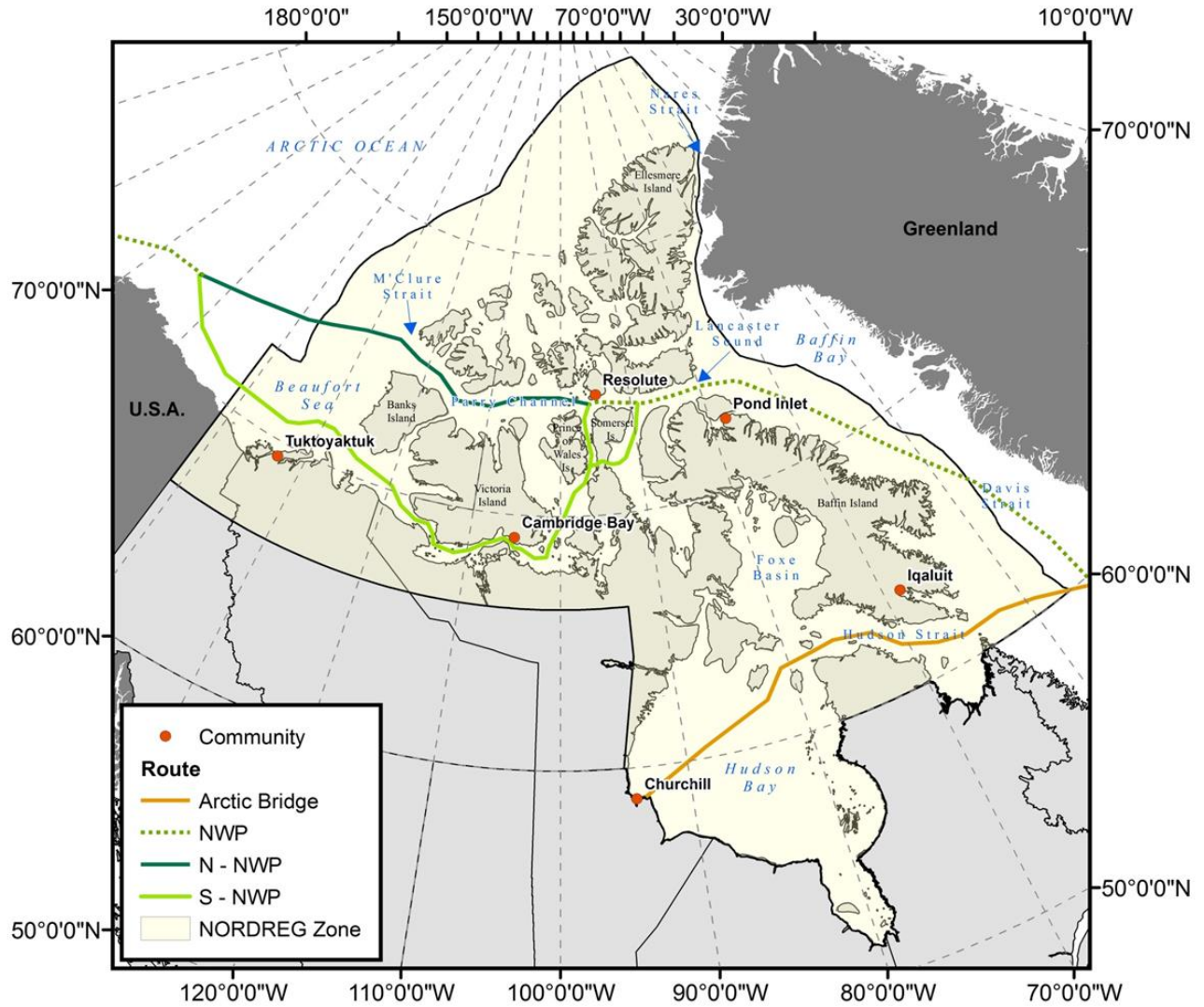
A special mention to all of my fellow lab mates of both LCR and ESPG (especially Olivia Mussells and Wesley Van Wychen!) and fellow cryosphere colleagues (Alex Zahara!) who listened to countless hours of troubleshooting, brainstorming, and frustrations about what the best way would be to "*connect the dots*"! Last but certainly not least, I would like to extend a very special thank-you to all my family and friends who supported me throughout this entire process, you are all amazing!

## **CHAPTER 1: Introduction**

The physical environment of the Arctic is experiencing some of the most rapid environmental changes of all regions globally (Jeffries et al., 2013; Derksen et al., 2012). This is having significant implications for the polar marine environment, including sea ice conditions within the Canadian Arctic, which in turn is influencing a number of socio-economic changes such as increased tourism demand and potential for natural resource development (Dawson et al., 2014; Lasserre and Têtu, 2015; Guy, 2006; Prowse et al., 2009). With respect to sea ice, pan-Arctic shifts from a predominantly thick perennial sea ice regime to a younger, thinner, more seasonal sea ice regime is occurring (Parkinson, 2014; Comiso, 2012; Maslanik et al., 2011). Ice cover thinning can be explained by several factors including the fact that multi-year ice (MYI) coverage in the Canadian sector of the Arctic Ocean has declined by 83% from 2002 to 2009 (Maslanik et al., 2011), and that an extension of the melt season length pan-Arctic wide of 5 days decade<sup>-1</sup> occurred from 1979 to 2013 (Stroeve et al., 2014). Specifically, along the Arctic Bridge (AB) shipping route between 1960 and 2008, declines in summer sea ice of 11% and 15% decade<sup>-1</sup> were found, along with declines between 6% and 10% decade<sup>-1</sup> along the southern Northwest Passage (NWP) route over the same time period (Tivy et al., 2011a). No significant changes were identified for the northern NWP route (Tivy et al., 2011a). Moreover, coincident with declines in sea ice, several studies suggest that a seasonally sea ice-free summer (sea ice extent < 1.0 million km<sup>2</sup>) will be realized in the Arctic by mid-21<sup>st</sup> century (Wang and Overland, 2012; Massonnet et al., 2012). In turn this has led to suggestions of easier Arctic shipping activity across the Northern Sea Route (NSR), and NWP (e.g., Smith and Stephenson, 2013; Stephenson et al., 2013; Stephenson et al., 2011).

## *1.1 Study Area*

The study area for this project is the Northern Canada Vessel Traffic Services Zone (NORDREG zone) maritime region. This region encompasses all Canadian Arctic waters including two well-known Canadian Arctic shipping corridors: the Northwest Passage (NWP) and the Arctic Bridge (AB) (Figure 1.1). The NWP connects the Atlantic and Pacific oceans via Baffin Bay in the Eastern Arctic and the Beaufort Sea in the Western Arctic through two distinct routes: the northern route, and southern route (Figure 1.1). The northern deep water route extends through Parry Channel and terminates in M'Clure Strait, whereas the southern shallow water route extends from Baffin Bay to the Beaufort Sea via Lancaster Sound through Eastern Parry Channel, then south along the eastern coast of Prince of Wales Island, and lastly westwards along the southern coasts of Victoria and Banks Island into the Beaufort Sea (Figure 1.1). Conversely, the AB connects Europe and Eurasia to the Port of Churchill, Manitoba through Hudson Strait and into Hudson Bay (Figure 1.1).



*Figure 1.1. Map of NORDREG zone study area outlining the two major Canadian Arctic shipping routes: the northern NWP route (N-NWP), the southern NWP route (S-NWP) and the Arctic Bridge (AB) (CCG, 2013; Howell and Yackel, 2004).*

## *1.2 Sea Ice of the Canadian Arctic*

Across the Canadian Arctic the sea ice regime is highly variable seasonally and spatially with respect to its age, area, and extent (Tivy et al., 2011a; Melling, 2002). Importantly, there are significant differences between sea ice regimes of the NWP and Arctic Bridge (AB) shipping routes. By mid-January the entire Canadian Arctic and Hudson Bay is almost entirely ice covered, although at other times of year there is noticeable regional variability with ice persisting throughout the summer in some regions (e.g., Western Arctic), and nearly open water conditions occurring in other regions (e.g., Hudson Bay and the Eastern Arctic) (Tivy et al., 2011a, b; Parkinson, 2014).

Within the Canadian Arctic Archipelago (CAA) and the channels of the NWP, sea ice is typically a mix between FYI and MYI, with most of the region experiencing a landfast sea ice regime from November to July (Melling, 2002). For most regions, annual sea ice minimum conditions are reached in September (Melling, 2002). Within the NWP alone, the northern and southern route experience unique sea ice regimes, with the southern route experiencing break-up earlier and freeze-up up later than the northern route. MYI within the northern NWP route is produced from both in-situ promotion of FYI to MYI, and the dynamic import of MYI from the Arctic Ocean that has formed along the western coast of the Queen Elizabeth Islands (Howell et al., 2009; Melling, 2002). The dynamic import of MYI as FYI declines at more southern latitudes which facilitate more open water conditions, and in-situ FYI aging to MYI, are likely responsible for the statistically insignificant declining trends of MYI in the northern NWP region (Howell et al., 2013b; Howell et al., 2009; Tivy et al., 2011a).

Sea ice of the central CAA is largely driven by thermodynamic processes, resulting in in-situ MYI formation, whereas in the western CAA it is influenced by both dynamic import of MYI and in-situ formation (Kwok, 2006; Howell et al., 2013a, 2015). The Eastern Arctic, however, experiences a predominantly seasonal sea ice regime which can clear entirely in the summer (CIS, 2011), with MYI in the region mostly attributed to dynamic import (Melling, 2002; Kwok, 2006). Baffin Bay is mostly open water in the summer, with the only MYI resulting from southwards advection through Nares Strait and some from Lancaster Sound (Tang et al., 2004). Over the entire CAA, the largest reductions in sea ice are attributed to FYI losses, likely in response to increasing spring surface air temperatures (Tivy et al., 2011a).

Hudson Bay experiences a completely seasonal sea ice cover which melts out every summer, meaning that any MYI within the region is a result of dynamic import via Foxe Basin (Tang et al., 2004). Within Hudson Bay, the Arctic Bridge shipping route has experienced statistically significant declines in all ice types of 11-15% over the period 1960-2008 (Tivy et al., 2011a). In addition, sea ice of South East Hudson Bay / James Bay breaks up earlier, and freezes up later than ice found in the North West Hudson Bay (CIS, 2011). Surface air temperatures within Hudson Bay have increased over the 1966 to 2007 time period with the fall season experiencing the greatest increases of  $\sim 0.4^{\circ}\text{C decade}^{-1}$ , compared to spring temperature increases of  $\sim 0.2^{\circ}\text{C}$  to  $\sim 0.3^{\circ}\text{C decade}^{-1}$  (Tivy et al., 2011a). Freeze-up dates between 1996-2010 (compared to 1980 to 1995) within Hudson Bay are occurring  $1.6 \pm 0.32$  weeks later than normal, with breakup occurring earlier ( $1.53 \pm 0.39$  weeks), largely in response to increasing surface air temperatures (Hochheim and Barber, 2014). This has led to an increase in the open water season by

approximately 3 weeks between 1996-2010 compared to 1980-1995, for both Hudson Bay and Foxe Basin, and nearly 5 weeks in Hudson Strait (Hochheim and Barber, 2014).

### ***1.3 Shipping in the Canadian Arctic***

With a thinning, declining sea ice extent and thickness (e.g., Howell et al., 2009; Pistone et al., 2014; Tivy et al., 2011a; Laxon et al., 2013; Comiso, 2012; Serreze et al., 2007), the prospect of increased maritime activity is attractive (Stephenson et al., 2011). Navigation connecting Asia and Eastern North America through the Arctic instead of the traditional routes through the Panama and Suez Canals can result in significant distance and cost savings (Lasserre and Têtu, 2015; Stephenson et al., 2011; Kohn et al., 2009; Somanathan et al., 2007; Guy, 2006). However, as enticing as these savings are, significant ice hazards (e.g., MYI, icebergs) remain (Kubat et al., 2007; Howell et al., 2015; Van Wychen et al., 2014), making the region arguably more dangerous to navigate. There is also an increased need for the development of uniform environmental protection standards, a shipping governance framework, and standards for ship and operator safety if maritime activity is going to increase. In addition, attention is needed given that these changes have implications for the economy, the environment, Northern communities, and tourism activity (Chircop, 2009; Dawson et al., 2007, 2014; Lasserre and Têtu, 2015).

Many different vessel types operate within the Canadian Arctic, each with unique operations and cargo (Table 1.1). The Canadian Arctic is home to over 100 000 Canadians, with many relying on ships as the primary means of transporting goods to service their communities as air, rail, and

motor vehicle transport is not available or is too expensive (Nunavut Bureau of Statistics, 2010; Hodgson, 2013). As a result, community re-supply needs via ships are crucial, and may rise should the population grow, or the needs of communities change (Hodgson et al., 2013; Prowse et al., 2009). Additionally, with some of the largest un-tapped oil and gas reserves in the world located within the Arctic, the potential for increased marine activity due to oil and gas exploration and extraction is also a possibility (Prowse et al., 2009). The prospective increase in Northern resource extraction projects (e.g., Baffinland Mary River Iron Ore Mine) and subsequent increases in export of raw goods and materials out of the North will not only increase regular bulk shipments, but will also likely require increased marine transportation during the construction phase of these projects (Hodgson et al., 2013). Small-scale commercial fishing operations within the Canadian Arctic are also expanding further north as ice-free conditions persist for longer (Hodgson et al., 2013). Cruise tourism (e.g., Pleasure Crafts and Passenger Ships) represents the largest recent increase in ship traffic in the Canadian North, and is expected to increase further (Dawson et al., 2007, 2014; Pizzolato et al., 2014; Hodgson et al., 2013, Lasserre and Têtu, 2015). Importantly, in the near future, destination traffic (e.g., transporting goods to Resolute Bay from Montreal, visiting certain sites) is also expected to increase within the Canadian Arctic to service the needs of communities, rather than a “boom” of commercial traffic using the NWP as a major shipping corridor instead of other routes (e.g., Panama Canal) (Hodgson et al., 2013).

**Table 1.1.** Description of different vessel types and their associated uses (compiled from Arctic Council, 2009, their Tables 5.2 and 8.1).

<b>Classification</b>	<b>Description</b>	<b>Examples of Ship Types</b>
Government Vessels and Icebreakers	<ul style="list-style-type: none"> <li>• Designed to move and navigate in ice-covered waters</li> <li>• Must have a strengthened hull, an ice-clearing shape and the power to push through ice</li> </ul>	<ul style="list-style-type: none"> <li>• Coast guard</li> <li>• Icebreakers (Private, Research, Government)</li> <li>• Research vessels</li> </ul>
Container Ships	<ul style="list-style-type: none"> <li>• Cargo ships that carry their load in truck-size containers</li> </ul>	<ul style="list-style-type: none"> <li>• Cargo transport</li> </ul>
General Cargo	<ul style="list-style-type: none"> <li>• Carries various types and forms of cargo</li> </ul>	<ul style="list-style-type: none"> <li>• Community re-supply</li> <li>• Roll on/roll off cargo</li> </ul>
Bulk Carriers	<ul style="list-style-type: none"> <li>• Bulk carriage of ore (can carry oil or loose or dry cargo – not simultaneously with ore)</li> </ul>	<ul style="list-style-type: none"> <li>• Timber</li> <li>• Oil, Ore</li> <li>• Automobile carriers</li> </ul>
Tanker Ships	<ul style="list-style-type: none"> <li>• Bulk carriage of liquids or compressed gas</li> </ul>	<ul style="list-style-type: none"> <li>• Oil, natural gas, and chemical tankers</li> </ul>
Passenger Ships	<ul style="list-style-type: none"> <li>• Ships that carry passengers</li> </ul>	<ul style="list-style-type: none"> <li>• Cruise ships</li> <li>• Ocean liners</li> <li>• Ferries</li> </ul>
Tug / Barge	<ul style="list-style-type: none"> <li>• Tug: Designed for towing or pushing, and general work duties</li> <li>• Barge: non-propelled vessel for carriage of bulk or mixed cargo</li> </ul>	<ul style="list-style-type: none"> <li>• Re-supply vessels</li> <li>• Bulk cargo transport</li> </ul>
Fishing Vessels	<ul style="list-style-type: none"> <li>• Fishing boats are used in commercial fishing activity</li> <li>• Generally small vessels, between 30 meters but can be as large as 100 meters</li> </ul>	<ul style="list-style-type: none"> <li>• Small fishing boats</li> <li>• Trawlers</li> <li>• Whaling boats</li> <li>• Fish processing boats</li> </ul>

<b>Classification</b>	<b>Description</b>	<b>Examples of Ship Types</b>
Oil and Gas Exploration Vessels	<ul style="list-style-type: none"> <li>• Designed specifically for the exploration and extraction of natural gas and oil</li> </ul>	<ul style="list-style-type: none"> <li>• Seismic, Oceanic, and Hydrographic Survey vessels</li> <li>• Oil drilling/storage vessels</li> <li>• Offshore re-supply</li> <li>• Portable oil platform vessels</li> <li>• Other oil and gas support vessels</li> </ul>
Pleasure Crafts	<ul style="list-style-type: none"> <li>• Small vessels engaged in expedition-like tourism</li> </ul>	<ul style="list-style-type: none"> <li>• Personal yachts</li> <li>• Small cruise tourism vessels</li> </ul>

Although the potential benefits of Arctic shipping operations are alluring, there are significant risks and costs associated with undertaking these operations. Financial costs associated with Arctic shipping compared to conventional shipping operations include higher insurance premiums, manufacturing of ice-strengthened vessels, hiring trained ice pilots, and ice-breaking support services (Hodgson et al., 2013; Arctic Council, 2009). These high financial risks are further exacerbated by physical risks brought on by the lack of marine infrastructure to support shipping operations such as the lack of deep water port facilities, limited locations for refuelling, challenges with access to search and rescue services, and poorly charted waters (Arctic Council, 2009; Hodgson et al., 2013). Additional challenges include disruption to traditional land, invasive species entering Arctic waters from ballast water, disruption to marine habitat, hazards posed by sea ice and icebergs, and informal regulations with respect to polar shipping operations (Inuit Circumpolar Council, 2008; Arctic Council, 2009; Hodgson et al., 2013; Brigham, 2007, 2011; Dawson et al., 2014; Van Wychen et al., 2014; IMO, 2010, 2014). Importantly, from a logistics perspective, continued presence of sea ice will continue to present challenges compared

to the reliable southern routes for planning and scheduling of voyages (Liu and Kronbak, 2010; Schøyen and Bråthen, 2011).

This region also faces many unique regulatory challenges such as the question of who is responsible (financially and otherwise) for environmental disasters, and who should pay for the costs of search and rescue operations in the event of an emergency? To address some of these challenges, the International Maritime Organization has recently developed a Polar Code which would govern all aspects of shipping operations in polar ice-covered waters, including mechanisms for environmental protection, pollution prevention, search and rescue, ship design, and operational protocols (IMO, 2014). This builds upon existing international conventions (e.g., Safety of Life at Sea (SOLAS), United Nations Convention on the Law of the Sea (UNCLOS), The International Convention for the Prevention of Pollution from Ships (MARPOL)), but addresses unique concerns pertaining to polar shipping operations such as presence of sea ice, environmental sensitivity, and remoteness that poses challenges for quick emergency response (IMO, 2014; Arctic Council, 2009). Although there are many opportunities and challenges associated with an increase in Arctic shipping activity in Canada, changing sea ice dynamics represents an important enabler and inhibitor to the sector and it is a topic area that requires focused research to ensure effective policy development and risk management decision-making moving forward.

#### ***1.4 Interactions between Sea Ice and Shipping Activity***

Modelling studies show increased marine accessibility in the Arctic in the summertime, but other seasonal differences (e.g., changes in spring and fall shipping activity) have only recently been explored (Stephenson et al., 2013; Sou and Flato, 2009, Rogers et al., 2013). Importantly, models have difficulty resolving regional variability, which is critical given the potentially more mobile ice pack, import of thick MYI, and presence of ice hazards due to increased open water areas in the southerly channels of the CAA (Howell et al., 2009, 2013a, 2015). Similarly, Stephenson et al. (2013) suggest that accessibility within the NWP will decline between 2080–2099 compared to 2046–2065 as result of these hazardous conditions. Kohn et al. (2009) also suggest an increase in the navigable season through the NWP from 2 to 4 months by the end of the 21<sup>st</sup> century, citing similar concerns of MYI and mobile ice hazards for navigation.

Within Hudson Bay, the majority of ships transiting via the AB shipping route in the summer are not ice strengthened (Tivy et al., 2007). Earlier break up and later freeze up in this corridor therefore provides the potential for an extended open water shipping season, with predictions of an ice-free season extending by over 2 months under the warming climate scenario described by Joly et al. (2011) (Markus et al., 2009, Stroeve et al., 2014).

#### ***1.5 Research Objectives and Organization of Thesis***

This thesis is presented in article-based format, and addresses two inter-related research objectives aimed at developing a greater understanding of how shipping activity is changing across the Canadian Arctic, and whether or not these changes are related to changing sea ice,

surface air temperatures, and the melt season length. Previously, only modelled studies explored the interactions between sea ice, shipping, and the surrounding physical environment (e.g. Smith and Stephenson, 2013), and this thesis is the first to explore these interactions on an observational basis over a 23 year time period (*Chapter 2*). Furthermore, *Chapter 3* presents a methodology for integrating sea ice conditions, bathymetry, and proximity to land to effectively connect known ship points to generate historical ship tracks using a LCP approach to improve upon existing methods which connect known ship points using a straight line (i.e. Halpern et al., 2008). Employing an alternative to the straight line approach in the Canadian Arctic was necessary as the abundance of islands within the Canadian Arctic Archipelago (CAA) result in numerous ship tracks traversing land. Thus, the development of an alternative LCP methodology suitable for use in the Canadian Arctic context was essential for the accurate reconstruction of historical ship tracks.

Objective 1 is to quantify temporal changes in sea ice and shipping activity from 1990 to 2012 using observational datasets. This manuscript presents the first long-term time series of changes to shipping activity in the Canadian Arctic while exploring linkages to sea ice, melt season length, and changing surface air temperatures. Objective 1 is addressed in *Chapter 2*, and the manuscript has been published in *Climatic Change* as:

Pizzolato, L., Howell, S. E. L., Derksen, C., Dawson, J., & Copland, L. (2014). Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. *Climatic Change*, 123(2), 161–173. doi:10.1007/s10584-013-1038-3.

The final publication is available at <http://link.springer.com/article/10.1007%2Fs10584-013-1038-3>.

Objective 2 is presented in *Chapter 3* and presents a Least Cost Path (LCP) approach to reconstruct historical ship tracks from point data. This chapter further validates the ability of the LCP methodology to undertake subsequent spatial analysis using an independent Automatic Information System (AIS) dataset from 2010. This manuscript is prepared for submission, and is entitled:

*Generation of Arctic Shipping Routes in Canada using a Least Cost Path Approach: Case Study for 2010*. The co-authors on this manuscript are Drs. Jackie Dawson, Luke Copland, and Stephen Howell.

### ***1.6 Authorship and Co-author Contributions***

I am the first author on both manuscripts included as *Chapters 2* and *Chapter 3* within this thesis, performed all of the data analysis, and contributed significantly to the methodology design and writing of the final manuscripts. Methodology for *Chapter 2* was designed in partnership with Drs. Stephen Howell and Chris Derksen from Environment Canada's Climate Research Division, and written/revised with the input of Drs. Stephen Howell, Chris Derksen, Jackie Dawson, and Luke Copland. Two anonymous reviewers are also thanked for their contributions to the final manuscript. The methodology for the LCP vessel track reconstruction and validation in *Chapter 3* was designed in conjunction with Drs. Luke Copland, Stephen Howell and Jackie Dawson, and written/revised with the input of Drs. Jackie Dawson, Luke Copland, and Stephen Howell.

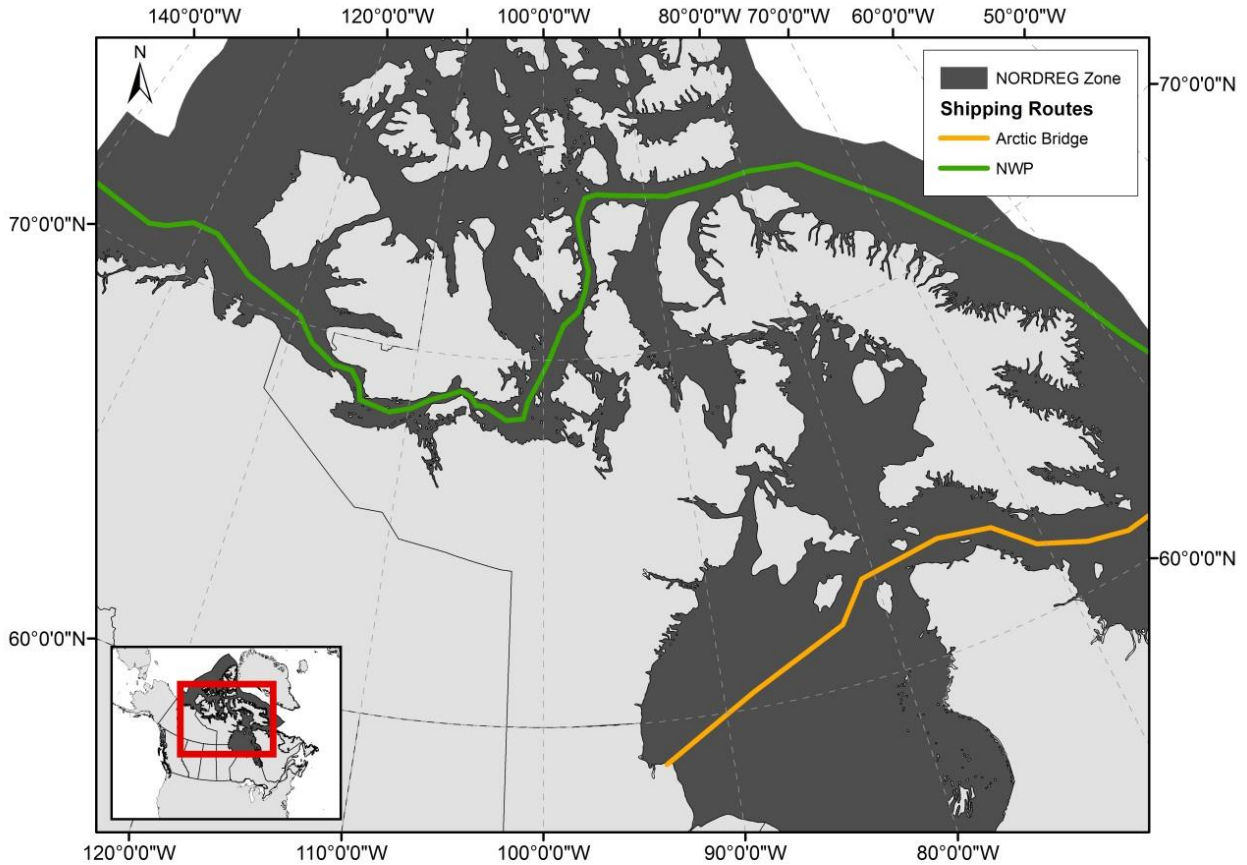
## **CHAPTER 2: Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012**

### ***2.1 Abstract***

Declining sea ice area in the Canadian Arctic has gained significant attention with respect to the prospect of increased shipping activities. To investigate relationships between recent declines in sea ice area with Arctic maritime activity, trend and correlation analysis was performed on sea ice area data for total, first-year ice (FYI), and multi-year ice (MYI), and on a comprehensive shipping dataset of observed vessel transits through the Vessel Traffic Reporting Arctic Canada Traffic Zone (NORDREG zone) from 1990 to 2012. Links to surface air temperature (SAT) and the satellite derived melt season length were also investigated. Between 1990 and 2012, statistically significant increases in vessel traffic were observed within the NORDREG zone on monthly and annual time-scales, coincident with declines in sea ice area (FYI, MYI, and total ice) during the shipping season and on a monthly basis. Similarly, the NORDREG zone is experiencing increased shoulder season shipping activity, alongside an increasing melt season length and warming SAT. Despite these trends, only weak correlations between the variables were identified, although a step increase in shipping activity is apparent following the former summer sea ice extent minimum in 2007. Other non-environmental factors have also likely contributed to the observed increase in Arctic shipping activity within the Canadian Arctic, such as tourism demand, community re-supply needs, and resource exploration trends.

## ***2.2 Introduction***

Two major shipping routes extend through Canadian Arctic waters, the Northwest Passage (NWP), and the Arctic Bridge (Figure 2.1). Navigating through the Arctic via the NWP provides an alternative shipping route to the Panama Canal which can potentially result in distance savings. The Arctic Bridge shipping route provides a corridor between the Russian port of Murmansk and Churchill, Manitoba. The use of these northern shipping routes can thereby provide an economic advantage compared to conventional routes at lower latitudes. The remoteness, harsh maritime conditions, and presence of ice hazards increase the risk of undertaking shipping operations in the Arctic. Considerations for investment in improved port infrastructure, resource extraction, tourism, community re-supply, research activities, search and rescue capacity, and ice-breaker support services among other marine services and regulations, will therefore be vital to ensure safe transits through Arctic waters without detrimental impacts on the environment, residents, wildlife, and human safety (Rompkey and Cochrane, 2008; Arctic Council, 2009; Dawson et al., 2007; IMO, 2010).



**Figure 2.1.** Map of the NORDREG zone boundary and Arctic Shipping Routes, derived using the CISIRR, Canadian Coast Guard NORDREG zone, and AMSA Shipping Routes (CCG, 2013; Arctic Council, 2009).

Sea ice extent and volume in the Arctic is experiencing a decline in all months of the year (e.g., Serreze et al., 2007; Stroeve et al., 2012; Comiso, 2012; Laxon et al., 2013). In Canadian Arctic waters, sea ice has also declined, with some of the strongest negative trends in Hudson Bay and Baffin Bay (Tivy et al., 2011a; Derksen et al., 2012), both of which are regions of heavy shipping activity. Some global climate models project that the Arctic could be ice-free in

September as early as 2030 (Wang and Overland, 2012). The continued reduction of sea ice within the Arctic based on future model projections has attracted considerable attention, and it has been suggested that these declines will have profound impacts on increasing accessibility for Arctic marine shipping activities (e.g., Stephenson et al., 2011; Smith & Stephenson, 2013). While logical, these suggestions have been largely speculative because they are based on climate and transportation model simulations that only consider physical changes in sea ice cover. There have been few studies that have directly compared measured changes in sea ice area and actual shipping numbers. Moreover, when model simulations predict sea ice-free conditions as early as 2030 they are referring to sea ice extent  $< 1$  million km<sup>2</sup>. Any remaining summer sea ice will be adjacent to, and within, the Canadian Arctic Archipelago (CAA) (see Wang and Overland, 2012) which contains the oldest and thickest multi-year ice (MYI) in the world (Maslanik et al., 2011; Melling, 2002; Bourke and Garrett, 1987). As the transition to ice-free summertime conditions continue, MYI will therefore likely continue to pose a hazard to vessel transits in Canadian Arctic waters, especially within the NWP as it will continue to flow southward from the Arctic Ocean (Melling, 2002; Howell et al., 2009; Howell et al., 2013a). Despite these concerns, a fundamental question remains unanswered - have the observed decreases in Arctic sea ice cover over the past two decades resulted in increased shipping activity? This study uses observational data to address this question by investigating changing patterns of ship activity in the Canadian Arctic in relation to changes in sea ice area from 1990 to 2012.

## ***2.3 Data Description***

### **2.3.1 Vessel (NORDREG) Dataset**

Within the Vessel Traffic Reporting Arctic Canada Traffic Zone, commonly known as the NORDREG zone (Figure 2.1), an extensive record of Arctic marine transportation activities was acquired from the Canadian Coast Guard for 1990 to 2012 across all months of the year. The dataset provides positional data daily, and upon entry and exit into/out of the NORDREG zone, in addition to vessel name, call sign, International Maritime Organization (IMO) number, and flag state for each reporting record (CCG, 2013). Although not mandatory for all vessels to report to NORDREG, there is a reported 98% compliance in the NORDREG reporting system due to the advantages accompanied with participation such as icebreaker support (Rompkey and Cochrane, 2008). Vessel types were re-classified from the original 36 NORDREG classifications into 10 categories based on their purpose, and unique environmental threats posed to the surrounding marine environment using the Arctic Marine Shipping Assessment (AMSA) vessel classification categories (Arctic Council, 2009; Table 2.1).

**Table 2.1. NORDREG Vessel Type Classifications grouped into 10 categories.**

<b>AMSA Classification</b>	<b>Reporting Records<sup>1</sup></b>	<b>Unique Vessels<sup>2</sup></b>	<b>Original Classification in the NORDREG Dataset</b>
Bulk Carriers	7932	291	Bulk Carrier, Grain Ship (Churchill)
Fishing Vessels	10817	171	Fishing Vessels
General Cargo	12904	53	General Cargo, Heavy Lift Ship, Heavy Load Vessel, Heavy Load Carrier Ship
Government Vessels and Icebreakers	23093	105	CCG Icebreaker, Icebreaker, USCG(C) Icebreaker, USCG Cutter, CCG Vessel, Fisheries Patrol Vessel, CCG Nav aids, SAR Vessel, Navy Ship, Fisheries Research Vessel
Oil/Gas Exploration/Exploitation	80	8	Drill Ship, Drill Rig, Oceanographic Research Vessel, Seismic Research Vessel
Passenger Ships	4632	36	Passenger Ships
Pleasure Crafts	1898	110	Pleasure Craft, Sail/Row Boat, Row Boat, Pleasure Crafts, Home Made Boat
Tanker Ships	8565	100	Chemical Tanker, Tanker
Tugs/Barges	12622	102	Tug, Tug/Supply, Tug/Icebreaker, Self-Powered Barge, Powered Barge
Other	12	1	Cable Ship

<sup>1</sup> Total reporting records included in the analysis over the 1990 – 2012 study period.

<sup>2</sup> Total unique vessels over the entire 1990 – 2012 study period.

Vessel counts within the NORDREG zone were established based on unique record entries for a given vessel call sign, IMO (International Maritime Organization) number, and vessel name in any given month and year.

Extensive quality control was performed on the NORDREG vessel dataset prior to analysis to ensure that any spelling errors and discrepancies in vessel classification were addressed using cross-validation of vessel IMO number, call sign, and vessel name. After removing vessels with missing or unrecognizable date fields, insufficient spatial information, and those outside of the NORDREG study area, a total of 82 555 reporting records of 129 603 original records were included in the analyses. In addition, one Cable Ship with 12 records was classified into the “Other” category as it did not fall into the AMSA vessel classification.

For vessel specific analysis, the vessel types: “Oil/Gas Exploration/Exploitation” and “Other” were removed as these classes contained too few records to perform robust statistical analyses. The remaining 8 categories: Bulk Carriers, Fishing Vessels, General Cargo, Government Vessels and Icebreakers, Passenger Ships, Pleasure Crafts, Tanker Ships, and Tugs/Barges were used in the vessel specific monthly and annual analyses. This incorporated 968 unique vessels, by vessel name, of the original 977 in the database (Table 2.1). For non-specific vessel analysis, the “Oil/Gas Exploration/Exploitation” and “Other” vessel classes were included in annual and monthly vessel counts as they still represent vessels within in the NORDREG zone. Vessel counts are reported as the unique presence of a vessel either monthly or annually based on the name of the vessel. For example, if a ship entered and exited the NORDREG zone multiple times in the same month, it was counted as one vessel in that month.

A change in NORDREG legislation on July 1, 2010 introduced daily positional mandatory reporting for vessels of 300 gross tonnage or more, vessels engaged in towing or pushing another

vessel if the combined gross tonnage is 500 gross tonnage or more, and vessels carrying, towing, or pushing a vessel carrying cargo that is a pollutant or dangerous good (CCG, 2013). To assess the potential impact on the dataset of the change from voluntary to mandatory vessel reporting, the Rodionov statistical regime shift detector was applied to the vessel report time series, with cut-off values ranging from 4 to 16 years in intervals of 2, and a Hubers weight parameter of 2 (Rodionov, 2004). These 7 cut-off values, representing years, provide a broad range of thresholds to detect regime shifts at varying time scales at a 95% confidence level or higher. The regime shift detector does not require *a priori* hypotheses on the timing of regime shifts, and can detect shifts of different time scales and magnitudes through modifying the cut-off lengths and the Huber's weight parameter (standard deviations from the mean). The Huber's weight parameter was set to 2 to reduce the magnitude of outliers on the detection of regime shifts, as values outside of 2 standard deviations of the mean are weighted inversely proportional to the distance from the expected mean value of the new regime (Rodionov, 2004).

### **2.3.2 Sea Ice Dataset**

The sea ice data used in the analysis were acquired from the Canadian Ice Service Digital Archive (CISDA) which contains weekly regional ice charts derived from surface observations, aerial and satellite reconnaissance, operational model results, and ice forecaster knowledge for all months of the year extending from 1968 to present which improves spatial resolution instead of using passive microwave datasets exclusively (CIS, 2007; Tivy et al., 2011a). Using the CISDA regional ice charts improves upon the ability to resolve regional ice conditions and concentration during the melt season, in comparison to the passive microwave satellite record

which underestimate sea ice area due to water over ice contamination (Agnew and Howell, 2003). Analysis of the quality of the CISDA dataset performed by Tivy et al. (2011a) shows that biases in the dataset from technological advancements from 1979 to present do not introduce inhomogeneities to the time series, therefore it is appropriate for trend analysis during our study period.

Average sea ice area was extracted within the NORDREG zone at monthly, and shipping season, (June 25 to October 15) time scales for total ice area, MYI area (ice older than one year that has survived a melt season), and FYI area because they each pose unique challenges to Arctic transportation activities (Arctic Council, 2009).

### **2.3.3 Ancillary Datasets**

Estimates of the melt season length and surface air temperature (SAT) were used to assist in understanding the relationship between sea ice and shipping vessel counts. The melt season length was estimated by taking the difference between sea ice melt onset and freeze onset from satellite passive microwave measurements as described by Markus et al., (2009). 2011 and 2012 were not used in the analysis of melt season length due to erroneous values found in this year over Hudson Bay. Notably, freeze onset estimates along the coastlines are significantly earlier during 2011 and 2012 than all other years (it is unclear why; Jeffrey Miller-NASA Goddard, personal communication). Monthly mean SAT was utilized from National Centers for

Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis performed on 2.5 degree x 2.5 degree grid cells over the NORDREG zone (Kistler et al., 2001).

#### ***2.4 Analytical Methodologies***

The NORDREG shipping dataset, CISDA sea ice dataset, and SAT dataset did not meet the assumptions of statistical normality required for parametric linear trend analysis. Therefore, trend analysis was performed using a non-parametric approach that removes the serial correlation, accounts for the non-normality exhibited by the datasets, and reduces the impact of extreme values and outliers in the time series. The Zhang method was used to compute Sen's slope of the trend, also removing the lag-1 autocorrelation which was present in all datasets (Zhang et al., 2000). To ensure consistency in the analyses, Sen's slope of the trend was also used for the melt season length.

Kendall's tau rank correlation for non-parametric data was calculated for relationships between sea ice, melt season length, SAT, and vessel counts in the NORDREG zone on monthly, annually, and shipping season time scales. Lag correlations were performed for melt season length and for the role that September sea ice conditions may play in determining vessel traffic in the NORDREG zone the following year ('preconditioning'). The two-tailed T-test was used to determine the significance of the correlations at the 95% confidence level or higher. All of the datasets were detrended prior to performing correlation analysis to ensure relationships were not

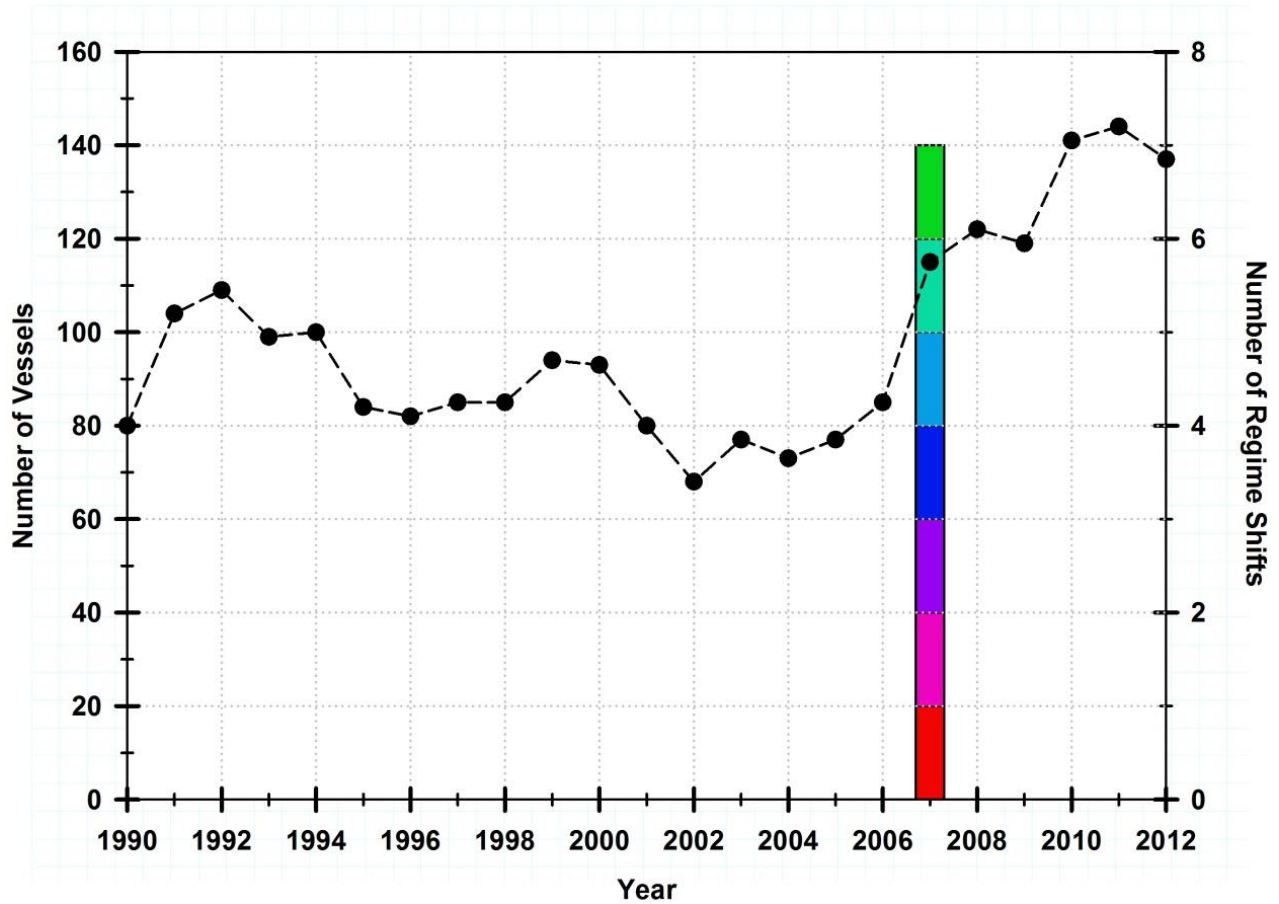
due to a shared trend, but rather driven by actual relationships between variability in the sea ice and marine vessel time series.

To determine the potentially increasing impact of extreme ice loss events and a changing sea ice age/area on shipping activities, moving window correlation analysis was undertaken using Kendall's tau rank based correlation. The original time series spans from 1990 to 2012, with each subsequent correlation recalculated through shortening the time series by one year from 1990 to the time period of 2002-2012, while ensuring a minimum of 10 years was used in each analysis (1990-2012, followed by 1991-2012, 1992-2012, etc.). Correlation confidence intervals at the 95% level were constructed using a confidence interval approximation described by Samra and Randles (1988), and Hollander and Wolfe (1973).

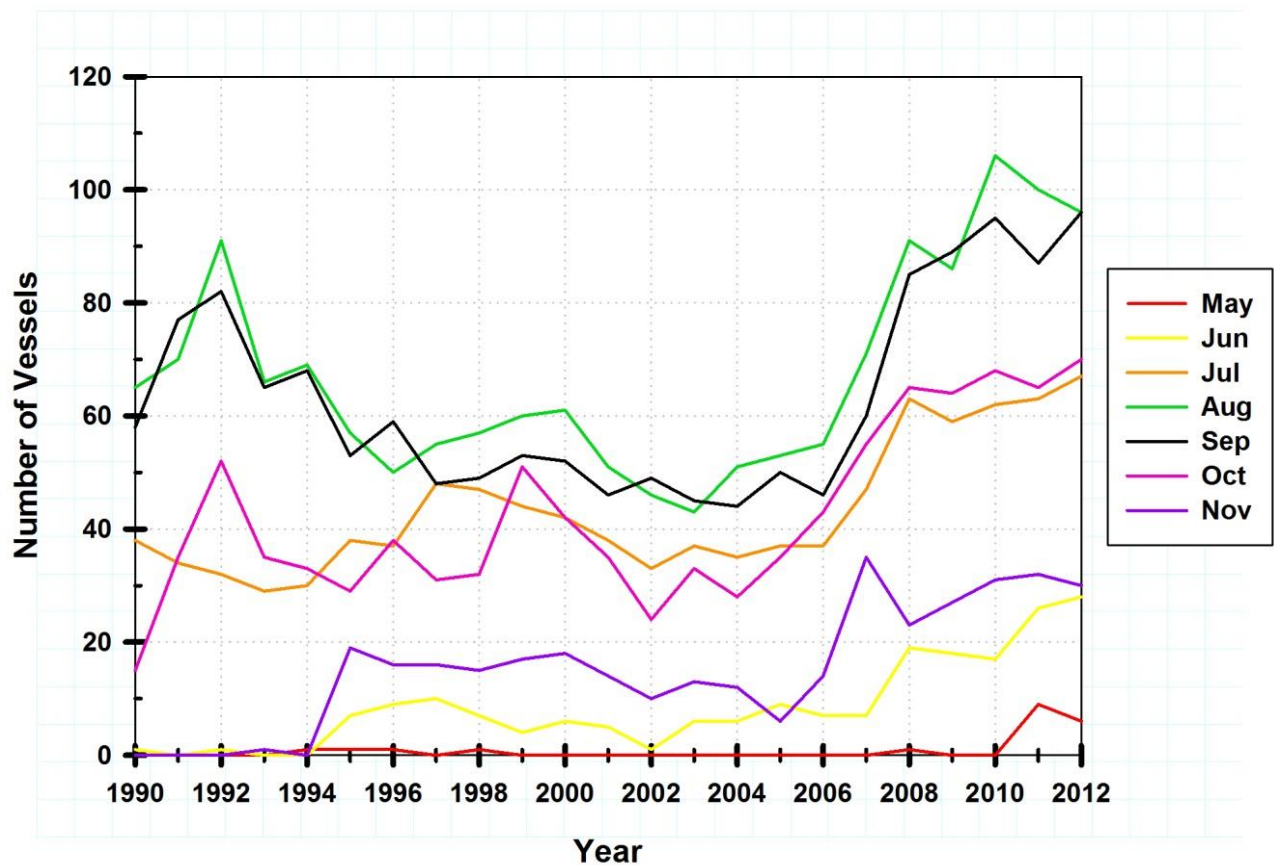
## ***2.5 Results***

### **2.5.1 Shipping Trends and Variability**

Arctic marine transportation activities in the NORDREG zone, as characterized by total vessel counts, have seen a sustained increase since 2007 (Figure 2.2). Increases in vessel counts in the June to October shipping season were also observed for 2009 through 2011 (Figure 2.3). Annual vessel count trends are increasing significantly (at the 95% confidence level) for Government Vessels and Icebreakers, and Pleasure Crafts at a rate that exceeds 8 vessels decade<sup>-1</sup> (Table 2.2). Bulk Carriers and Passenger Ships are also experiencing statistically significant increases of 3 vessels decade<sup>-1</sup> (Table 2.2).



*Figure 2.2. Regime shifts were detected for all cut-off values in 2007; no regime shifts were detected in any other year for annual vessel counts, 1990-2012. Cut-off values represent the number of years used in regime detection window thresholds.*



*Figure 2.3. Total monthly vessel counts from May through November in the NORDREG zone, 1990 – 2012.*

Positive trends in the total vessel count for all vessels over the entire year are not significant, but the monthly increases of 9 vessels decade<sup>-1</sup> in June, 22 vessels decade<sup>-1</sup> in July, and 13 vessels decade<sup>-1</sup> in November are significant, which seems to indicate operators are increasing their shipping season beyond the traditional June 25 to October 15 time frame (Table 2.2). Fishing Vessels, Tanker Ships, and Government Vessels and Icebreakers all exhibit significant increases in the June and November shoulder months, thus contributing to the significant increases in

overall vessel counts during these months which suggest the extension of the shipping season (Table 2.2).

*Table 2.2. Sen's slope of decadal vessel count trends in the NORDREG zone, 1990 - 2012.<sup>a, b</sup>*

Vessel Type	Trend (Vessels Decade <sup>-1</sup> )												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
All Vessel Types	0	-	-	-	0	<b>9</b>	<b>22</b>	27	51	22	<b>13</b>	0	24
Bulk Carriers	-	-	-	-	-	0	-1	0	0	2	<b>1</b>	0	<b>3</b>
Fishing Vessels	0	-	-	-	0	<b>6</b>	5	13	3	0	5	0	-2
General Cargo	-	-	-	-	-	-	-	-	-	-	-	-	1
Government Vessels and Icebreakers	-	-	-	-	-	<b>1</b>	<b>3</b>	<b>3</b>	<b>2</b>	<b>4</b>	<b>1</b>	0	<b>8</b>
Passenger Ships	-	-	-	-	-	-	2	2	3	0	-	-	<b>3</b>
Pleasure Crafts	-	-	-	-	-	-	<b>1</b>	<b>18</b>	<b>4</b>	0	-	-	<b>8</b>
Tug/Barge	-	-	-	-	-	0	<b>3</b>	2	3	<b>7</b>	0	-	4
Tanker Ships	-	-	-	-	-	<b>2</b>	<b>2</b>	0	6	0	<b>1</b>	0	1

<sup>a</sup> Bold values are significant at the 95% confidence level or higher.

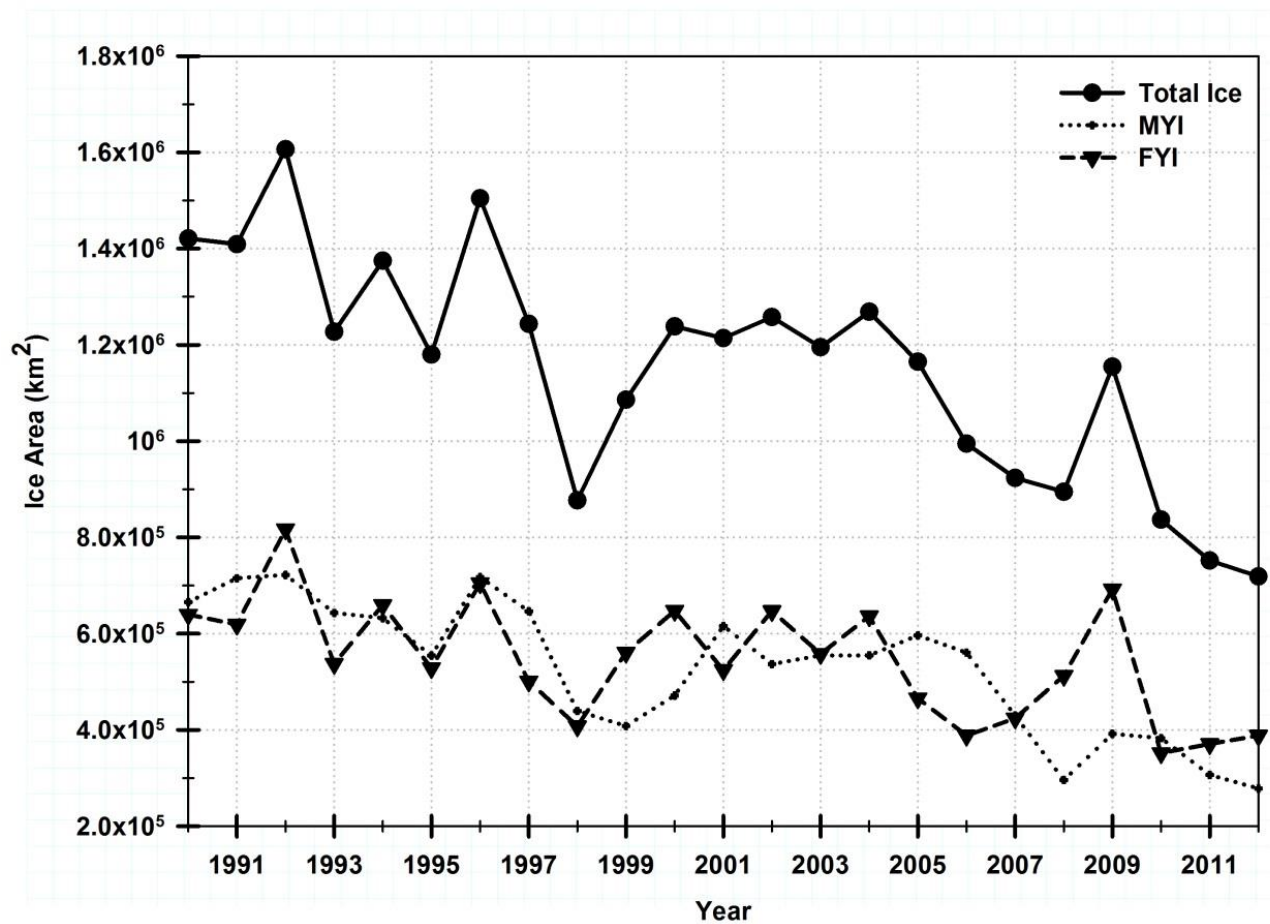
<sup>b</sup>“-” indicates no trend.

Annually, for all vessel counts, a regime shift was detected in the vessel count time series in 2007 at all of the cut-off values (Figure 2.2), coinciding with what at the time was a record low September Arctic sea ice minimum (Stroeve et al., 2008), since broken in 2012 (Zhang et al., 2013). The magnitude and consistent detection by all cut-off values of the regime shift in 2007 provides evidence that the change in mandatory vessel reporting in 2010 does not artificially introduce a trend into the dataset. Specifically, if the changes in reporting resulted in a significant increase in the number of vessels, significant regime shifts would have been observed in 2010 or 2011, which is not the case (Figure 2.2).

### **2.5.2 Sea Ice Trends and Variability**

Over the shipping season, sea ice within the NORDREG zone is characterized by statistically significant declines of total ice, MYI, and FYI area at  $30 \times 10^3 \text{ km}^2 \text{ year}^{-1}$ ,  $19 \times 10^3 \text{ km}^2 \text{ year}^{-1}$  and  $11 \times 10^3 \text{ km}^2 \text{ year}^{-1}$ , respectively (Figure 2.4). This is an important result for shipping activities, especially for MYI, which represents the most hazardous ice type for vessels. Significant decreases in summer FYI from 1990 – 2012 ( $-19 \times 10^3 \text{ km}^2 \text{ year}^{-1}$  for July,  $-13 \times 10^3 \text{ km}^2 \text{ year}^{-1}$  for August, and  $-6 \times 10^3 \text{ km}^2 \text{ year}^{-1}$  for September respectively) indicate that more FYI is melting during the summer months, which contributes to reductions in MYI areas for the subsequent shipping season because less FYI survives the melt season for promotion to MYI (Table 2.3). However, the recent increases in areas of open water in the lower latitudes of the CAA facilitates the southward import of MYI from the Arctic Ocean into the CAA, and subsequently into the channels of the NWP thus still posing a navigational hazard for shipping operations (Howell et al., 2013a). Monthly mean total sea ice area in the NORDREG zone is

declining significantly in all months of the year with the exception of April, with greatest losses from June to December exceeding  $-19 \times 10^3 \text{ km}^2 \text{ year}^{-1}$  to a maximum of  $-34 \times 10^3 \text{ km}^2 \text{ year}^{-1}$  in July (Table 2.3). Mean MYI is experiencing a significant decline in all months of the year in excess of  $-10 \times 10^3 \text{ km}^2 \text{ year}^{-1}$  in June, to a maximum of  $-23 \times 10^3 \text{ km}^2 \text{ year}^{-1}$  in October (Table 2.3). Declining total ice, MYI and FYI area within the NORDREG zone from 1990 to 2012 is in agreement with current model simulations (Stephenson et al., 2013; Stephenson et al., 2011; Sou and Flato, 2009).



**Figure 2.4.** Time series of shipping season mean total ice, MYI, and FYI area (km<sup>2</sup>) in the NORDREG zone, 1990 – 2012.

**Table 2.3.** Sen's slope trends for mean monthly and shipping season (June 25 to October 15) sea ice area within the NORDREG zone, 1990 - 2012.<sup>a</sup>

Month	Trend Ice Area (x 10 <sup>3</sup> ) km <sup>2</sup> year <sup>-1</sup>			Month	Trend Ice Area (x 10 <sup>3</sup> ) km <sup>2</sup> year <sup>-1</sup>		
	Total Ice	MYI	FYI		Total Ice	MYI	FYI
January	<b>-8</b>	<b>-14</b>	3	August	<b>-29</b>	<b>-17</b>	<b>-13</b>
February	<b>-7</b>	<b>-13</b>	3	September	<b>-28</b>	<b>-22</b>	<b>-6</b>
March	<b>-5</b>	<b>-13</b>	5	October	<b>-27</b>	<b>-23</b>	-3
April	-1	<b>-13</b>	4	November	<b>-24</b>	<b>-21</b>	-9
May	<b>-9</b>	<b>-11</b>	1	December	<b>-15</b>	<b>-18</b>	-6
June	<b>-19</b>	<b>-10</b>	-5				
July	<b>-34</b>	<b>-14</b>	<b>-19</b>	Shipping Season	<b>-30</b>	<b>-19</b>	<b>-11</b>

<sup>a</sup> Bold values are significant at the 95% confidence level or higher.

### **2.5.3 Relationships between Arctic Shipping, Sea Ice and the Atmosphere**

The relationships between shipping season mean total ice, MYI, and FYI area and annual vessel counts revealed weak significant correlations (at the 95% confidence level or higher) for some vessel types for total ice area: Government Vessels and Icebreakers (-0.34), and Passenger Ships (-0.34), and General Cargo (-0.30). MYI area relationships also revealed weak significant correlations for: General Cargo (-0.40), Government Vessels and Icebreakers (-0.30), Passenger Ships (-0.30) (Table 2.4). Similarly correlations between monthly mean total ice and MYI area, and monthly vessel counts in the NORDREG zone revealed significant correlations for some vessel types in the months of July through October which fall within the traditional shipping season, June 25 to October 15 (Table 2.4). Outside of the traditional shipping season, weak positive correlations were identified between total ice area and Pleasure Crafts in March and February at 0.30 and 0.34 respectively, as well as relationships between total ice area and Bulk Carriers, and the total for all vessel types in November at -0.30. No additional correlations were discovered between monthly sea ice area and monthly vessel counts from January to June, and November to December, signifying ice conditions alone are not contributing to the observed monthly vessel count increases outside of the traditional shipping season. No correlations were found between annual and monthly vessel counts and FYI area.

**Table 2.4.** Kendall's Tau Correlations for mean monthly sea ice area ( $\text{km}^2 \text{ year}^{-1}$ ) and monthly vessel counts in the NORDREG zone for July through October, 1990 - 2012.<sup>a,b</sup>

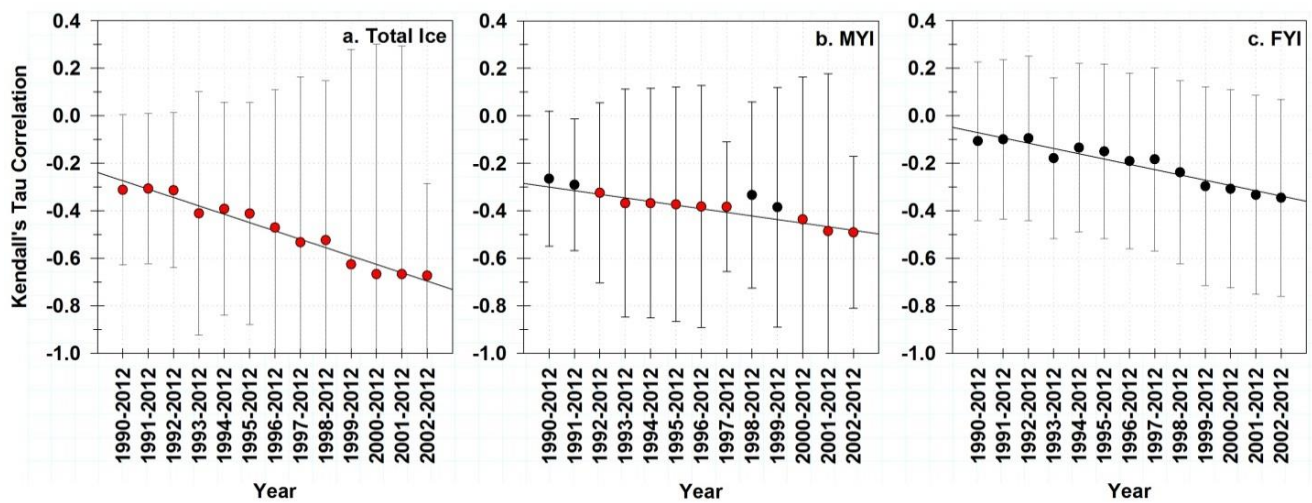
Vessel Type	Ice Area ( $\text{km}^2 \text{ year}^{-1}$ )									
	Total					MYI				
	Jul	Aug	Sep	Oct	Shipping Season	Jul	Aug	Sep	Oct	Shipping Season
All Vessel Types	-0.22	-0.23	-0.19	0.00	<b>-0.31</b>	<b>-0.32</b>	<b>-0.44</b>	-0.19	-0.15	-0.26
Bulk Carriers	-0.01	-0.04	0.08	<b>0.30</b>	0.04	-0.16	-0.23	-0.02	0.19	-0.07
Fishing Vessels	-0.23	-0.22	-0.09	-0.02	-0.19	-0.13	<b>-0.38</b>	-0.08	0.00	-0.14
General Cargo	-0.29	-0.26	<b>-0.30</b>	-0.15	<b>-0.30</b>	-0.28	<b>-0.38</b>	<b>-0.37</b>	<b>-0.34</b>	<b>-0.40</b>
Government Vessels and Icebreakers	0.14	-0.14	<b>-0.31</b>	-0.15	<b>-0.34</b>	0.18	-0.14	<b>-0.36</b>	-0.27	<b>-0.30</b>
Passenger Ships	-0.11	-0.19	-0.17	0.09	<b>-0.34</b>	-0.10	-0.29	-0.12	-0.08	<b>-0.30</b>
Pleasure Crafts	-0.14	-0.12	0.04	-0.04	-0.07	<b>-0.38</b>	-0.23	-0.02	0.21	-0.10
Tug/Barge	0.00	0.01	-0.01	-0.03	-0.21	-0.25	-0.19	-0.01	-0.08	-0.10
Tanker Ships	-0.23	-0.01	-0.15	-0.01	-0.19	-0.26	-0.23	-0.15	-0.04	-0.19

<sup>a</sup> Bold values are significant at the 95% confidence level or higher.

<sup>b</sup> No correlation is identified by “-”.

Successively stronger negative correlations between total ice area and annual vessel counts have occurred over the entire time series at the 95% confidence level or higher (Figure 2.5) with the strongest correlation reported during the 2002-2012 time period of -0.69 . Between 1992 – 2012 and 2002 – 2012 (with the exception of 1998-2012 and 1999 – 2012), correlations between mean MYI area and annual vessel counts also exhibited an increasingly strong negative trend towards present with the strongest negative correlation reported during the 2002-2012 time period at -

0.56. These correlations indicate that the statistically significant relationship between total ice area/MYI area and annual vessels in the NORDREG zone has become progressively stronger over the 1990 to 2012 time period. The increasingly strong negative relationship between annual vessel counts and mean total sea ice area/MYI area over the entire time series provides a compelling argument for an increasingly favourable environment for maritime activity in the Canadian Arctic.



**Figure 2.5.** Moving window Kendall's Tau correlation analysis to measure the relationship between shipping season mean ice area (a. Total, b. MYI, c. FYI) and annual vessel counts in the NORDREG zone. Red markers denote significant correlations at the 95% confidence level or higher. Confidence intervals become increasingly larger as the time series shortens as we become less confident in the correlations due to the smaller sample size.

Increasing trends in SAT were observed in January, February, and July through October at a rate of 0.7°C to 1.8°C decade<sup>-1</sup> with the greatest increases observed in the fall and winter months (not

shown). These increasing SAT trends across the NORDREG zone are consistent with SAT trends in the Northern Polar Area of  $0.6^{\circ}\text{C decade}^{-1}$  (Winter),  $0.7^{\circ}\text{C decade}^{-1}$  (Spring),  $0.4^{\circ}\text{C decade}^{-1}$  (Summer), and  $0.8^{\circ}\text{C decade}^{-1}$  (Fall) reported by Bekryaev et al. (2010) for the period 1979-2008. The extension of the shipping season is consistent with an increasing mean annual melt season length of  $11 \text{ days decade}^{-1}$ , and delay in the mean freeze onset date (as determined from the satellite passive microwave record) of  $8 \text{ days decade}^{-1}$ . This relates to significant correlations (at the 95% confidence level or higher) between shipping season total sea ice area and melt season length (-0.51), melt onset (0.53), and freeze onset (-0.31). Increasingly, the trends in later freeze up and increasing SAT in the fall and winter months (that exceed those in the spring or summer), suggest that the extension of the shipping season is driven largely by changes during the fall.

Evidence of freeze onset preconditioning the following year's monthly vessel counts only exists for total November and December counts with correlations of 0.34 and 0.45 respectively (significant at the 95% confidence level or higher), suggesting a later freeze onset may be linked to an extension of the shipping season into the November shoulder season. Freeze onset from the previous year (e.g., 2010) preconditioning annual vessel counts in the following year (e.g., 2011) revealed relationships for specific classes: General Cargo (0.37), and Tanker Ships (0.38).

In terms of the role of an earlier melt onset preconditioning the number of vessel counts in the NORDREG zone, significant correlations (at the 95% confidence level or higher) were identified for Passenger Ships annually (-0.46) and the total for all vessel types in May (-0.32). This

provides evidence to suggest that earlier melt onset may be related to an increase in vessel traffic in the NORDREG zone early in the season. Additionally, no relationships between lag correlations of freeze onset and melt season length (1990-2010) preconditioning September and shipping season mean total, MYI or FYI sea ice area (1991-2011) were discovered. Importantly, the lack of strong significant correlations between decreasing sea ice and increasing shipping activities over the 1990 to 2012 shipping season provide some evidence to support the hypothesis that shipping activities are not planned solely based on the condition of the sea ice but rather also consider external factors likely relating to resource development, shipments to communities, cargo delivery, and improvements in vessel design (e.g., Arctic Council, 2009; Lasserre and Pelletier, 2011; Rompkey and Cochrane, 2008).

## ***2.6 Conclusions***

Vessel reporting records for the NORDREG zone, and the CISDA, collectively provided the opportunity to quantitatively address speculation that recent changes in Arctic sea ice are, and will, lead to enhanced maritime activity in the Arctic. While changes in reporting practices occurred within the NORDREG dataset, statistical regime shift tests identified a break point in the time series coincident with the large-scale reductions in Arctic sea ice, notably in 2007, and not changes in vessel reporting. Non-parametric trend analysis identified increasing trends for vessel types annually, and monthly between June and November from 1990-2012, with monthly increases reported as high as 22 vessels decade<sup>-1</sup> in July for all vessel classes combined, and 8 vessels decade<sup>-1</sup> annually for Government Vessels and Icebreakers and Pleasure Crafts (Table 2.2). Significant increases in decadal vessel counts in the shoulder seasons for all vessel types

combined annually (Table 2.2), increasing SAT trends to a maximum of  $1.8^{\circ}\text{C decade}^{-1}$  in the winter months (not shown), and declining sea ice in all months of the year (e.g., Figure 2.4, Table 2.3) provide evidence of a lengthening shipping season. Moving window correlation analysis over the entire 1990 to 2012 time period showed that the strength of correlations between annual vessel counts and total ice area/MYI area increased over the past decade, likely due to the impact of recent reductions in sea ice area (Figure 2.5). The lack of correlation between increasing vessel count trends and sea ice trends over the full period of study suggests that (1) the major changes in sea ice conditions since 2007 resulted in a step change in shipping activities (Figure 2.2) and/or (2) external factors to sea ice conditions may be driving the observed increases in shipping traffic in the Canadian Arctic. In this regard, further attention is required to assess the relationships between infrastructure development, economic activities, and resource extraction in relation to vessel transits, including the spatial analysis of transit routes. Spatial variability in vessel activity is also important with respect to MYI, which continues to flow into the NWP as the transition to a sea ice-free summertime Arctic continues (Howell et al., 2013a).

This study has provided the first observational evidence of increasing maritime shipping activity in the Canadian Arctic. The direct linkage between maritime activity and sea ice is not statistically strong, likely because the environmental, economic, and logistical factors which influence Arctic shipping are complex. Sea ice conditions represent only one factor in the decision making process facing shipping operators among other safety and economic considerations linked with undertaking operations in the North (e.g., Lasserre and Pelletier, 2011). With the observed changes to Arctic sea ice area projected to continue during future

decades, coupled analysis of observed Maritime activity and sea ice characteristics will be necessary to inform environmental, economic, and policy decision making in the Canadian Arctic.

## **CHAPTER 3: Generation of Arctic Shipping Routes in Canada using a Least Cost Path**

### **Approach: Case Study for 2010**

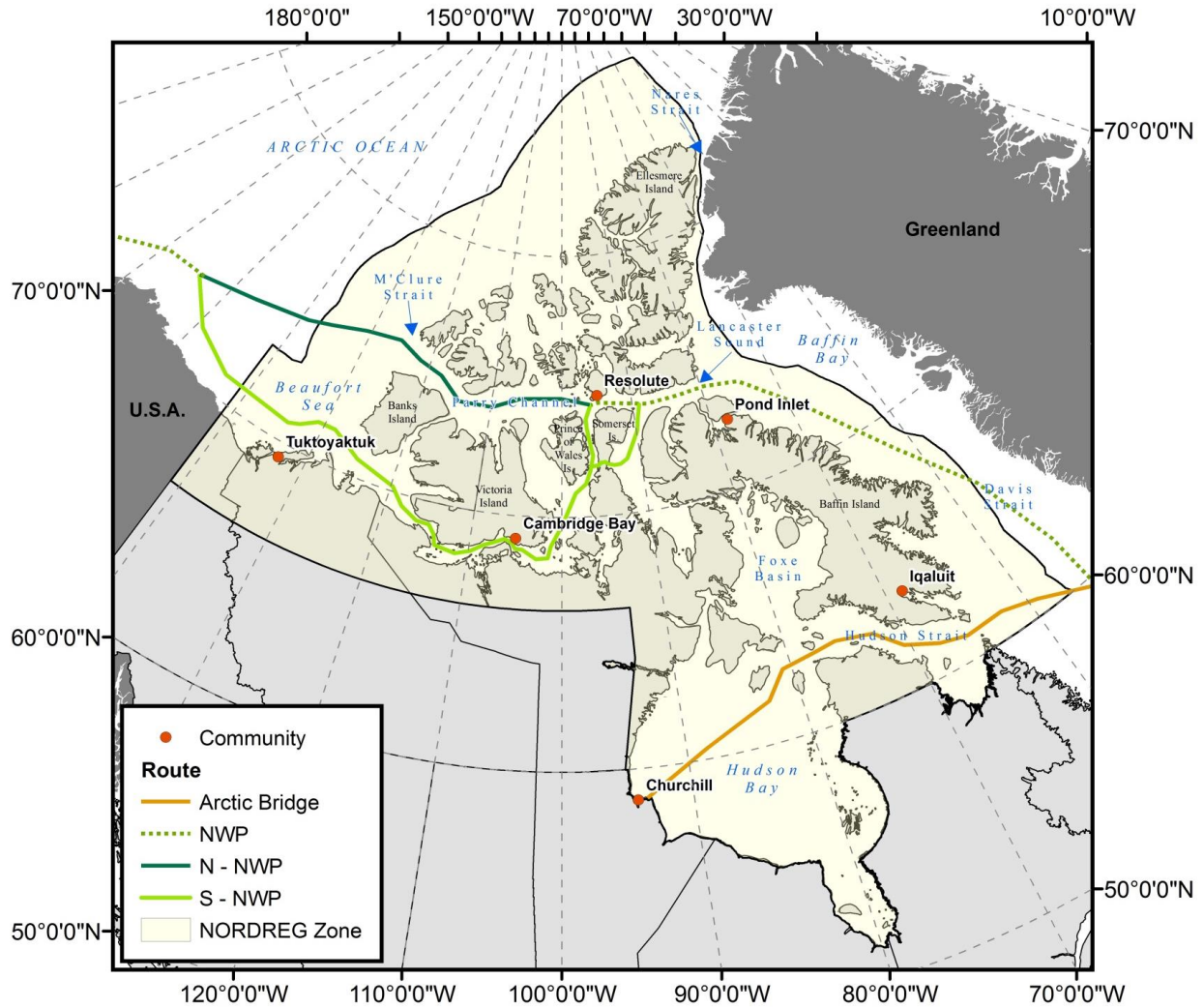
#### ***3.1 Abstract***

The Arctic is currently undergoing rapid environmental changes, and as a result the prospect of increased shipping activity within this region has been dominating discussions by industry, government, and academics alike. However, observational data of changing shipping patterns across the Canadian Arctic does not exist, and thus a method to derive historical shipping routes is necessary. Using a least cost path (LCP) approach integrating bathymetric, sea ice, and observational shipping data, we are able to successfully reconstruct historical shipping routes across the Canadian Arctic for 2010 from point data. 4217 voyage segments were reconstructed using the LCP approach. This approach was validated through comparing the NORDREG ship archive with the Automatic Identification System (AIS) independent ship point archive for a random subset of 25 vessel voyages. Error estimates were constructed based on the deviation of LCP derived ship routes compared to known locations within the AIS ship archive. The LCP approach was able to successfully reconstruct ship paths across the entire NORDREG zone at an accuracy of  $10.42 \text{ km} \pm 0.67 \text{ km}$ . This case study provides confidence that the LCP approach can be used to derive a 25 km gridded Canadian Arctic wide shipping product on an annual basis.

### **3.2 Introduction**

The sea ice of the Canadian Arctic is currently undergoing significant changes with respect to its dynamics, age, and extent, both spatially and seasonally. There are also significant differences in the seasonal evolution of the sea ice regime at different locations across the Arctic. For example, the NWP and Arctic Bridge (AB) shipping routes (Figure 3.1) each experience different sea ice conditions. By mid-January the entire Canadian Arctic and Hudson Bay is almost entirely ice covered, although at other times of the year there is marked regional variability with ice persisting through the summer in some regions (e.g., Western Arctic) where MYI exists, compared to nearly open water conditions in other regions (e.g., Hudson Bay and the Eastern Arctic) that are dominated by a mostly seasonal FYI cover (Tivy et al., 2011a,b). Sea ice minimum conditions occur in all regions in the month of September (CCG, 2012).

The Arctic shipping season is defined as the period between June 25<sup>th</sup> and October 15<sup>th</sup>, coinciding with the period of lowest annual sea ice conditions (following Tivy et al., 2011a), and contains the largest proportion of Arctic shipping activity throughout the year (*see* Figure 2.3). The entire Canadian Arctic has experienced declines of total ice coverage with Baffin Bay experiencing the strongest declines at  $-16.0\% \pm 4.1\% \text{ decade}^{-1}$ , followed by Hudson Bay at  $-15.7\% \pm 3.9\% \text{ decade}^{-1}$ , and lastly, the CAA at declines of  $-4.4\% \pm 2.0\% \text{ decade}^{-1}$  over the 1968 to 2008 period (Tivy et al., 2011a). Despite these strong declines, a reservoir of the oldest, thickest sea ice in the world remains along the northwestern edge of the Queen Elizabeth Islands (QEI) that will likely remain a hazard to shipping operations as MYI floes migrate southwards into the channels of the NWP and Canadian Arctic Archipelago (CAA) during the summer months (Melling, 2002; Howell et al., 2015).



*Figure 3.1. Map of NORDREG zone study area outlining the major Canadian Arctic shipping routes of the NWP northern route (N-NWP), southern NWP route (S-NWP), and the Arctic Bridge (AB) (CCG, 2013; Howell and Yackel, 2004).*

Potential for cost and distance saving exists with using Canadian Arctic shipping routes (or the more frequently travelled Northern Sea Route (NSR)) compared to the more common southern routes such as the Panama and Suez Canals (Liu and Kronbak, 2010; Guy, 2006). However, financial costs associated with Arctic shipping compared to conventional shipping operations

include higher insurance premiums, global economic trends (i.e., commodity, metal, and mineral prices), use of ice-strengthened vessels, ice pilots, and ice-breaking support services which can act as a deterrent to use of these Northern routes (Hodgson et al., 2013; Brigham, 2011; Arctic Council, 2009). These high financial risks are further exacerbated by physical risks brought on by the lack of marine infrastructure to support increased shipping operations in this region, such as the lack of deep water port and refuelling facilities, potentially long distances to search and rescue services, and poorly charted waters which increase grounding risks (Arctic Council, 2009). We know that shipping activity across the Canadian Arctic is increasing modestly (Pizzolato et al., 2014); however, current knowledge of the spatial distribution of shipping activity is largely unknown.

The objective of this Chapter is to explore the ability of least cost path (LCP) analysis to reconstruct historical Arctic ship routes for the future application of long term spatial analysis. This is necessary as the current shipping activity dataset, the NORDREG ship archive, exists with point data reported mostly on a daily basis, meaning that there are large gaps between the data points. Therefore, to better understand the spatial distribution of shipping activity across the Canadian Arctic, a method to connect the points to generate ship tracks is necessary. LCP analysis establishes the best route between two points based on a series of prescribed costs or hindrances to determine the most favourable route including: distance from land, bathymetry, and sea ice information. The LCP approach has previously been employed by Smith and Stephenson (2013) in their simulations of trans-Arctic mid-century shipping routes. Through the reconstruction of historical shipping routes using a LCP approach, we will be able to better understand the spatial variability of ship traffic across the Canadian Arctic.

### ***3.3 Study Area***

The Northern Canada Vessel Traffic Services Zone (NORDREG) encompasses all Canadian Arctic marine waters including two well-known Canadian Arctic shipping corridors: the NWP and the AB (Figure 3.1). The NWP connects the Atlantic and Pacific oceans via Baffin Bay in the Eastern Arctic and the Beaufort Sea in the Western Arctic through two distinct routes: the northern route, and southern route (Figure 3.1). The northern deep water route extends through Parry Channel and terminates in M'Clure Strait, whereas the southern shallow water route extends from Baffin Bay to the Beaufort Sea via Lancaster Sound through Eastern Parry Channel, then south along the eastern coast of Prince of Wales Island, and lastly westwards along the southern coasts of Victoria and Banks Island into the Beaufort Sea (Figure 3.1). Conversely, the AB connects Europe and Eurasia to the Port of Churchill, Manitoba through Hudson Strait and into Hudson Bay (Figure 3.1).

### ***3.4 Data Description***

#### **3.4.1 NORDREG Ship Archive**

The ship archive, provided by the Canadian Coast Guard, contains 89669 unique reported vessel locations and 4251 unique vessel voyages within the NORDREG zone over the period 1990 to 2013. This is a two part dataset, with the first part containing daily reports of vessel locations at 16:00 UTC for mandatory reporting vessels since 2010 (i.e., vessels that are 300 gross tonnes or more, engaged in towing or pushing another vessel if the combined gross tonnage is 500 gross tonnage or more, or if a vessel is carrying a pollutant or dangerous good, or towing a vessel

carrying a pollutant or dangerous good (CCG, 2013)). The dataset also contains voluntary reported ship positions within the NORDREG zone from 1990 to present, mostly on the daily or sub-daily timescale. The second part of the dataset includes a non-spatial ship archive containing vessel name, call sign, IMO number, entry and exit dates of the NORDREG zone, vessel length, width, and other non-spatial characteristics. Supplementary ship specification data was added to the previously quality controlled ship archive (see Pizzolato et al. 2014) to complete the dataset including ship draft, length, and width in addition to the marine mobile service identity number, MMSI, when available. This information came from various online government sources including: Transport Canada's Vessel Registration Query System (<http://wwwapps.tc.gc.ca/Saf-Sec-Sur/4/vrqs-srib/eng/vessel-registrations/>), Industry Canada's Spectrum Direct Ship Station Search ([https://sd.ic.gc.ca/pls/engdoc\\_anon/mmsi\\_search.Ship](https://sd.ic.gc.ca/pls/engdoc_anon/mmsi_search.Ship)), National Oceanic and Atmospheric Administration's (NOAA) Office of Science & Technology Vessel Documentation Search by Name (<http://www.st.nmfs.noaa.gov/st1/CoastGuard/VesselByName.html>), and freely available public websites including: Vessel Finder (<http://www.vesselfinder.com/>), Maritime Connector (<http://maritime-connector.com/ship/>), and ShipSpotting.com (<http://www.shipspotting.com/>). Both parts of the ship archive were then linked by a unique identifier based on year, vessel name, and voyage number as defined by a single entry and exit of the NORDREG zone.

### **3.4.2 AIS Ship Archive**

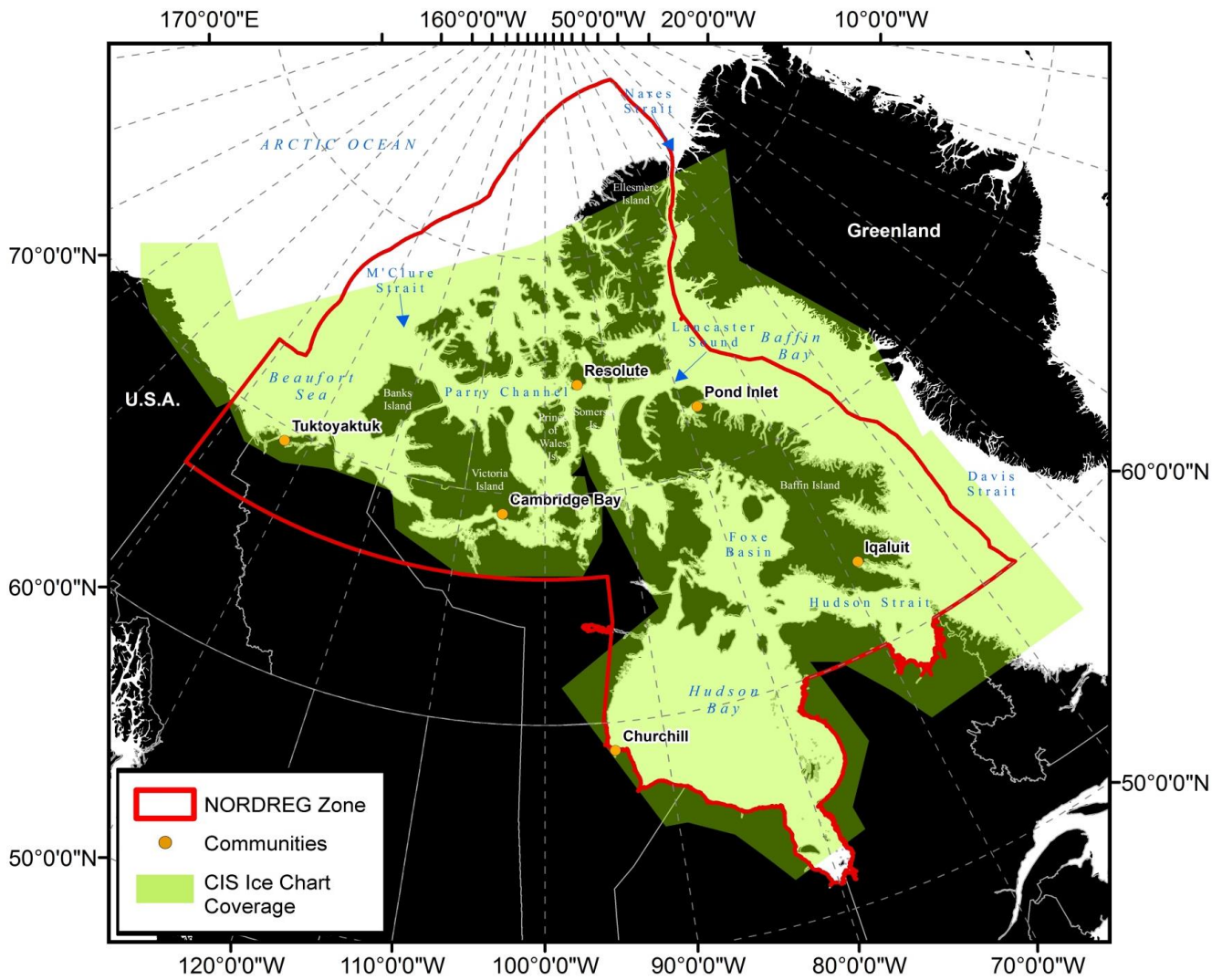
The Automatic Identification System (AIS) describes an automatic tracking system for ships which uses transponders to provide ship positions and ancillary information (e.g., speed, call

sign) via satellites and ground-based receivers at reporting intervals varying from hours to minutes. Higher reporting frequencies relate to periods when the AIS transponder is interrogated more frequently, such as in the presence of other ships in a busy port. AIS data records were provided by Transport Canada for 2010 to present, via the commercial provider exactEarth. Since July 1, 2008, under Canadian regulations for domestic voyages, all ships (excluding fishing vessels) that are 500 tons or more are required to carry an AIS transponder (TC, 2007). Furthermore, since 2002, mandated by the IMO, all ships on international voyages that are 300 tons or more (excluding fishing vessels), and ships that are 150 tons or more and carrying more than 12 passengers, are also required to carry an AIS transceiver (TC, 2007). The AIS dataset compliments the NORDREG dataset as it contains similar vessel data (MMSI, Date), but in some instances improves upon spatial resolution by providing more frequent position reports than the NORDREG ship archive. The AIS dataset also has some limitations as not all vessels carry AIS transponders, ships have the ability to turn the AIS system off, and there still remains some gaps between satellite passes, although this is improving as exactEarth and other providers improve their infrastructure capabilities (e.g., with the launch of additional satellites), with an anticipated revisit time of 1 hour in early 2016 (exactEarth, 2015).

### **3.4.3 Canadian Ice Service Digital Archive (CISDA)**

The Canadian Ice Service Digital Archive (CISDA), containing weekly regional ice charts, was used to extract total sea ice concentration for the entire study area (Figure 3.2). The weekly regional ice charts are derived from surface observations, aerial and satellite reconnaissance, operational model results, and ice forecaster knowledge from 1968 to present (CIS, 2007; Tivy et

al., 2011a). Furthermore, analysis of the quality of the CISDA by Tivy et al. (2011a) shows that biases in the dataset from technological advancements from 1979 to present do not introduce inhomogeneities to the time series, making it appropriate for use in the 2010 study period.



**Figure 3.2.** CISDA Weekly Regional Ice Chart Coverage over the NORDREG zone.

### **3.4.4 Bathymetry**

The ETOPO2v2 elevation and bathymetry dataset was used for the entire study area, acquired from the National Geophysical Data Center (NGDC) (*Data is located here:* <http://www.ngdc.noaa.gov/mgg/fliers/06mgg01.html>). This dataset, published in 2001 and revised in 2006, contains both terrain elevation and seafloor topography on a 2 Arc-minute grid, and a vertical precision of 1 m (NGDC, 2006). This dataset was derived from 6 assimilated bathymetric databases including Smith and Sandwell's 1978 satellite radar altimetry, International Bathymetric Chart of the Arctic Ocean (IBCAO), Global Land One-kilometer Base Elevation (GLOBE), and the NGDC Coastal Relief Model (NGDC, 2006).

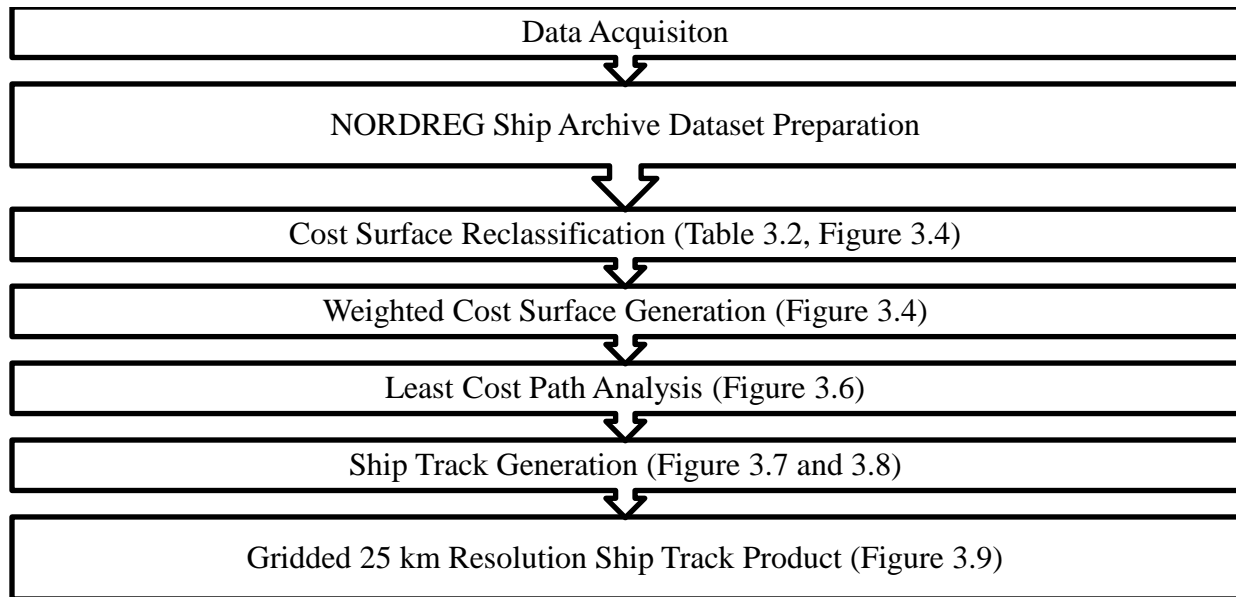
### **3.5 Case Study Selection**

For this case study, data from the year 2010 was used. The year 2010 was chosen because this was the first year that NORDREG reporting became mandatory for specific vessels (see *Section 3.4.1*), and secondly because this is the first year that available AIS and NORDREG data overlapped. Within the NORDREG spatial dataset, the year 2010 contained a total of 300 unique voyages and 6480 vessel reporting records. A total of 11 vessel voyages were not represented in the NORDREG spatial dataset but were present in the non-spatial dataset, and 4 were represented exclusively in the spatial dataset. Furthermore, 12 voyages only contained one reporting record in the NORDREG spatial dataset and were therefore unable to be reconstructed. Comparatively, for 2010, the AIS ship archive contained a total of 22 646 spatial data records, of which 13 624 contained the same MMSI number as vessels with known MMSI numbers within

the NORDREG spatial ship archive. This subset of AIS data (13 624 records) was used in the validation of LCP track reconstruction.

### ***3.6 Least Cost Path Reconstruction Methodology***

To identify where observed changes to shipping activity have occurred across the Canadian Arctic on an annual basis, the generation of voyage tracks was undertaken using a least cost path approach integrating three unique datasets: the Canadian Ice Service Weekly Regional Ice Charts, the ETOPO2v2 elevation and bathymetry dataset, and the NORDREG ship archive. All of the analysis was undertaken using ESRI ArcGIS 10.2, Python, and the ArcPy Python scripting module. The coastline mask used in the analysis was derived from the land mask used in the generation of the CISDA weekly regional ice charts. Using a LCP workflow, known vessel reporting records (points) are connected (by a line) based on a weighted cost surface (Table 3.2, Figures 3.3, 3.4, 3.6).



**Figure 3.3.** *Least cost path workflow.*

Costs are hindrances to the safe transit of a vessel and can be prescribed for any type of condition (e.g., a vessel cannot pass over land, vessels traverse through a certain concentration of sea ice more easily than others, or require a certain depth for safe transit). Therefore, the lower the cost surface, the more favourable the pathway is to connect known ship point records, and conversely the higher the cost, the less favourable the pathway. For each pair of points, a weighted cost surface was generated using three cost parameters: total sea ice concentration (total SIC; using the CISDA weekly regional ice chart nearest the date of the initial reported point), bathymetry, and distance from land. Each cost surface was then reclassified based on criteria in Table 3.2 using values between 0 and 100, with 0 signifying no cost, and 100 signifying maximum cost. All reclassified cost surfaces were sampled to a 1 km x 1 km raster surface by resampling the 25 km Equal-Area Scalable Earth Grid (EASE-Grid 2.0) prior to LCP analysis (Table 3.1).

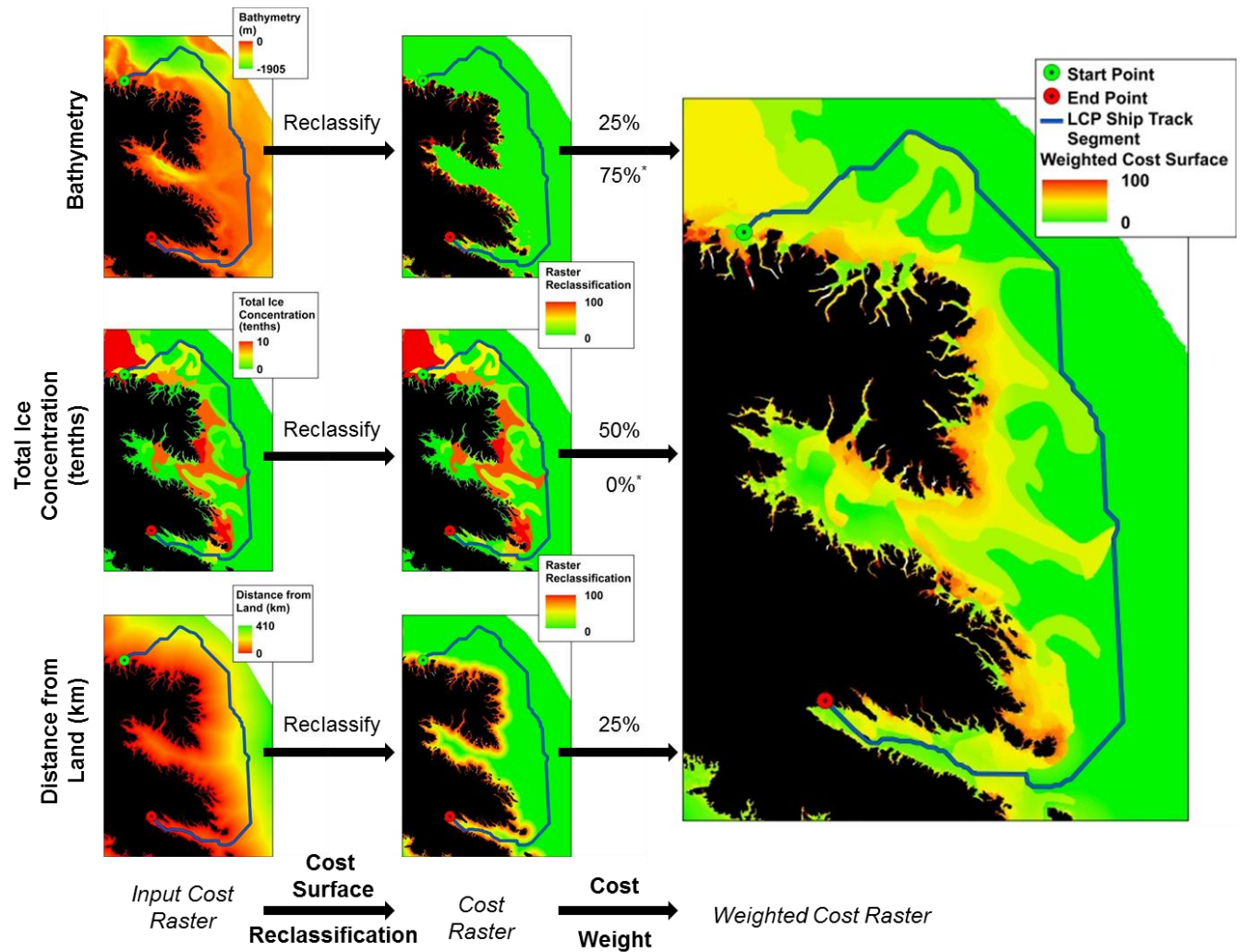
Subsequently, the weighted cost surface (now at a 1 km x 1 km resolution) was then used in the LCP analysis to establish a route between each pair of points (Table 3.1).

*Table 3.1. Spatial resolution, accuracy, and data format of LCP analysis data sources.*

Dataset	Original			Weighted Cost Surface		Final Product	
	Format	Resolution	Accuracy	Format	Resolution	Format	Resolution
<b>CISDA (Ice Charts)</b>	Vector	100 m <sup>a</sup>	+/- 0.5 km <sup>a</sup>				
<b>ETOPO2v2 (Bathymetry &amp; Elevation)</b>	Raster	~4 km <sup>b</sup>	~10 m <sup>b</sup>	Raster	1km	Raster	25 km EASE-Grid
<b>Distance from Land</b>	Raster	1km	N/A				

<sup>a</sup> (CIS, 2007)

<sup>b</sup> Error estimate acquired from <https://www.ngdc.noaa.gov/mgg/global/global.html>



\* Cost weight in the absence of ice information availability (see Figure 3.2).

**Figure 3.4.** Least cost path cost surface generation workflow.

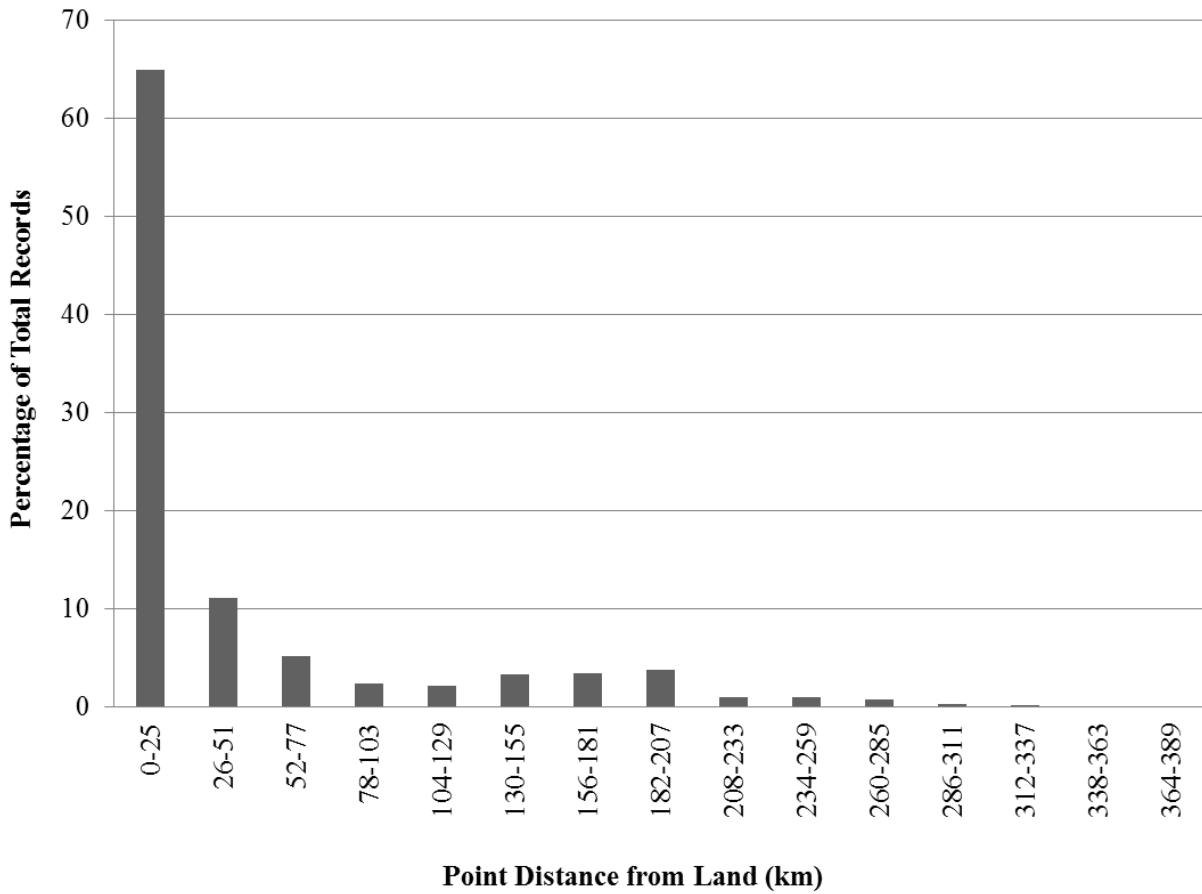
Total sea ice concentration was chosen as the ice cost parameter based on the *Ice Navigation in Canadian Waters* recommendation “Do not enter ice if an alternative, although longer, open water route is available” (CCG, 2012, p. 85). Moreover, this provided a cost surface using a conservative approach, by considering the contribution of both FYI and MYI equally in the ice cost surface generation. Even within a region of high FYI concentration, the presence of any

MYI remains a severe threat to ship navigation (CCG, 2012), and thus total SIC incorporating both MYI and FYI was employed as the ice cost parameter in the LCP analysis. Therefore,  $0_{/10}$  to  $1_{/10}$  ice concentration were assigned a cost of 0 (as these are the most favourable open-water and ice free conditions), total SIC of  $2_{/10}$  was assigned a cost of 50, increasing to a cost of 100 for  $10_{/10}$  total SIC (CCG, 2012; Table 3.2).

For the cost surface related to bathymetry, the maximum draft was established based on the known ship draft plus 3 m of under keel clearance. This clearance was chosen based on the most conservative values used for operations in the St. Lawrence River, as no such value was available for Arctic Waterways (CCG-DFO, 2015). The minimum draft is the known ship draft as recorded in the NORDREG ship archive (*see Section 3.4.1*). In cases where vessel draft data was not available for use in the LCP generation, 8 m was prescribed for the minimum draft of the vessel based on the mean value of known draft data for 596 unique vessels over the entire 1990 to 2013 dataset, and 11 m for the maximum draft following the 3 m safe under keel clearance.

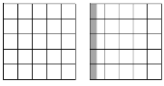









A cost surface for distance from land was established based on the criteria that any area further than 25 km away from land has no cost, and any area between 0 to 25 km away from the coast has a cost decreasing from 100 (at the coastline) to 0 (25 km away from the coast and beyond) (Table 3.2). This weighting scale was chosen based on three criteria: 1) LCP tracks avoid a path directly along the coastline unless absolutely necessary as it is unlikely that ships travel directly along the edge of the coastline; 2) coastal contamination within the 25 km x 25 km pixel of the final gridded product is accounted for to ensure that a more favourable voyage track exists

beyond cells that contain the coastline; 3) 65% of all reported NORDREG records are within 0 and 25 km of the coastline (Figure 3.5).



**Figure 3.5.** Point distance from coastline for all NORDREG records (Percentage of total records derived from n= 89 669)

**Table 3.2. Least cost path cost surface reclassification.**

<b>Total SIC</b>	<b>Graphic of Total SIC</b>	<b>*Ice Description</b>	<b>Cost</b>	<b>Bathymetry (- values) Elevation (+ values)</b>	<b>Cost</b>	<b>Distance from Land</b>	<b>Cost</b>
0-1		Ice Free/ Open Water	0	-3818 m to Maximum Draft	0	> 25 km	0
2		Very Open Drift	50	Maximum Draft to Minimum Draft	25	25 km to 0 km	Increasing linearly from 0 at 25 km from the coastline to 100 at the coastline
3			55	Minimum Draft to 0 m	50		
4		Open Drift	60	0 m to 1257 m	100		
5			65				
6			70				
7			85				
8		Close Pack	90				
9			100				
10		Very Close Pack to Compact	100				

\* Derived from CCG, 2012

Once calculated, all three reclassified cost surfaces were integrated into a weighted cost surface (Figure 3.4). When total SIC information was available (see Figure 3.2 for ice chart coverage), the final weighted cost surface consists of 50% sea ice information, 25% bathymetry and 25% distance from land:

$$W_{Cost\ Surface} = (50)W_{Total\ SIC} + (25)W_{Bathymetry} + (25)W_{Distance\ from\ Land} \quad [1]$$

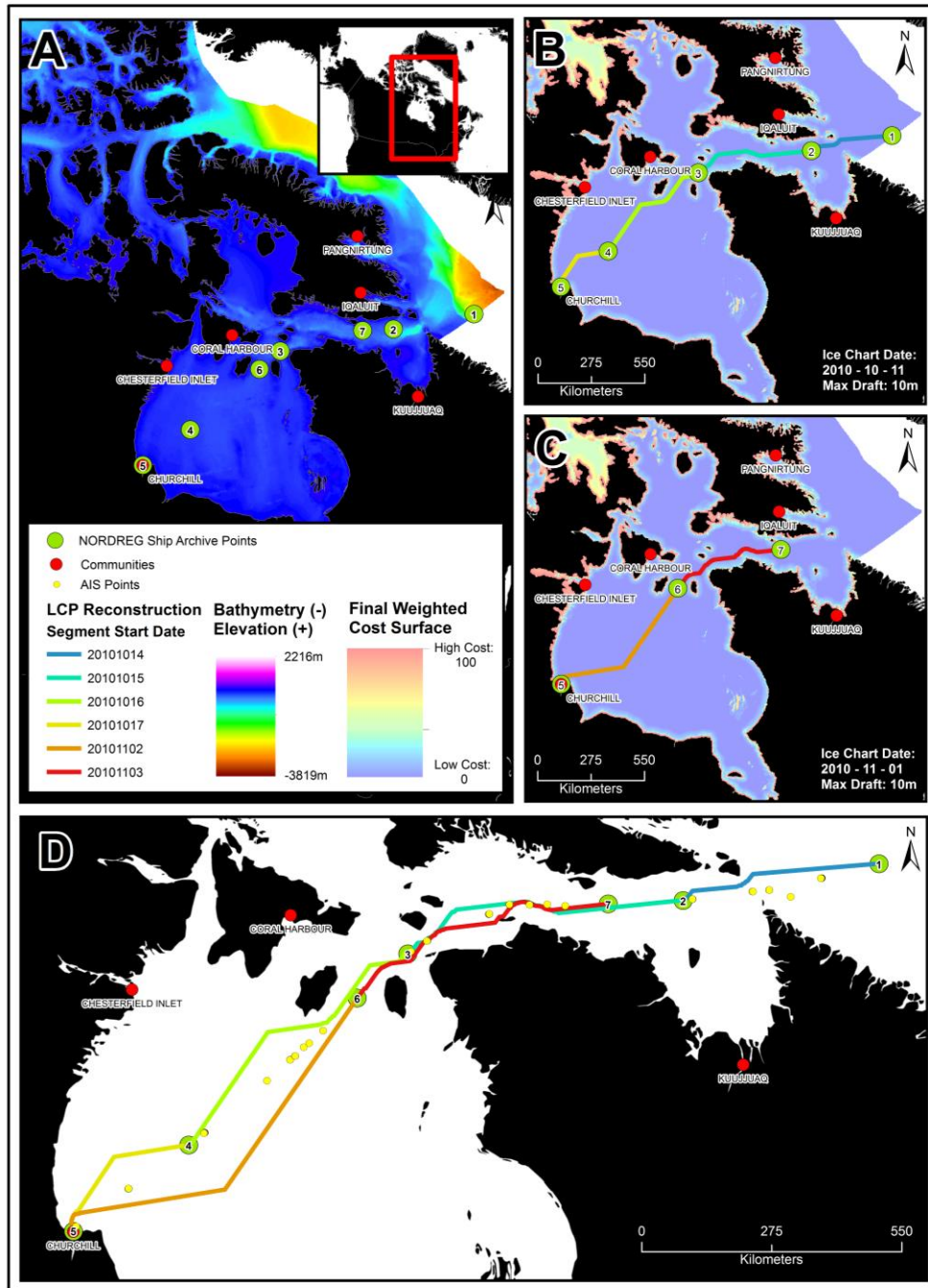
For areas in the NORDREG zone where sea ice information was not available, the weighted cost surface consisted of 75% bathymetry and 25% distance from land:

$$W_{Cost\ Surface} = (75)W_{Bathymetry} + (25)W_{Distance\ from\ Land} \quad [2]$$

In equations [1] and [2],  $W_{Total\ SIC}$  is the weighted total SIC cost surface,  $W_{Bathymetry}$  is the weighted bathymetry cost surface, and  $W_{Distance\ from\ Land}$  is the weighted distance from land cost surface.  $W_{Cost\ Surface}$  is the final weighted cost surface used in the LCP analysis for each set of points. The  $(50)_{Total\ SIC}$ ,  $(25)_{Bathymetry}$ ,  $(25)_{Distance\ from\ Land}$  weighting proportions in equation [1], and  $(75)_{Bathymetry}$ ,  $(25)_{Distance\ from\ Land}$  in equation [2] were chosen based on the relative impedance to a ships safe routing for each of the criteria. For example, in the presence of sea ice, the sea ice criterion is more heavily weighted (50%) as this contributes to an immediate threat to safe vessel transit, followed by the bathymetry and distance from land. As a result, this would weight an area with equally sufficient depth and distance from land that has sea ice present less favourably than an area that is absent of sea ice. Furthermore, the  $(75)_{Bathymetry}$ ,  $(25)_{Distance\ from\ Land}$  proportions

in equation [2] were chosen to illustrate the relative importance of each criterion in the ship routing, with sufficient depth being paramount, followed by distance from land.

A LCP segment using the aforementioned weighted cost surfaces (Figure 3.4, Table 3.2, equations 1 and 2) was used to connect known points using a cost path algorithm for each pair of points in the NORDREG ship archive for the year 2010 (Figure 3.6). For example, if a voyage contained three known points, two LCP segments would be generated between points 1 and 2, then again between points 2 and 3 (see Figure 3.6B, C). These segments were then merged to create a route for the entire vessel voyage throughout the NORDREG zone (e.g., Figure 3.6D).



**Figure 3.6.** (A) NORDREG ship archive points for one vessel voyage. (B) Weighted cost surface for a vessel with a maximum draft of 10 m, and for the ice chart dated October 11th, 2010 showing the associated LCP reconstructed segments. (C) Weighted cost surface for a vessel with a maximum draft of 10 m, and for the ice chart dated November 1st, 2010 showing the associated LCP reconstructed voyage segments. (D) Comparison of the LCP reconstructed vessel voyage segments to the known AIS points on the same date.

Once all of the LCP segments were generated for all the ship point records in the spatial NORDREG ship archive, the generated ship tracks were extracted to the 25 km National Snow and Ice Data Center (NSIDC) Equal-Area Scalable Earth Grid (EASE-Grid 2.0). The length of each individual voyage segment (in km) within each 25 km x 25 km cell was then calculated. The 25 km x 25 km EASE-Grid was selected for three reasons: 1) this is a commonly used grid that sea ice products are provided in, 2) the error estimates generated between known ship positions and generated LCP tracks are within the 25 km x 25 km grid cell (see details below), and finally, 3) computationally, a 25 km x 25 km grid over the entire Canadian Arctic domain is a suitable compromise between a comprehensive shipping activity inventory and the computational processing time that it takes to derive the ship tracks. Subsequently, the sum of all voyage segment lengths within each cell was calculated to provide a proxy for the amount of shipping activity that occurred within each cell for that year.

### **3.6.1 Validation**

To assess the ability for LCP analysis to predict vessel voyage pathways using the weighted cost surfaces outlined in equations [1] and [2], a random sample of 25 LCP derived vessel voyage routes were selected from the year 2010. These vessel voyages were represented in both the NORDREG and the AIS ship archives, and represent all of the AMSA vessel classes with the exception of two: Oil/Gas Exploration/Exploitation and Other. These 25 voyages consisted of 617 LCP generated voyage segments. The distance from each independent AIS data source was calculated to the nearest generated LCP voyage segment for the same date (see Figure 3.6D). This value represents the displacement from the known AIS point to the generated LCP segment.

The mean displacement was calculated for the sample of known AIS points ( $n = 925$ ) to the LCP generated voyage segments, then a Margin of Error,  $ME$ , was constructed at the 95% confidence level for the 25 voyages across the study area (Figure 3.1, equation [3]).

$$ME_{95} = t^* \left( \frac{\sigma}{\sqrt{n}} \right) \quad [3]$$

In equation [3],  $ME_{95}$  represents the Margin of Error (i.e., 95% confidence that the true mean displacement falls within the mean plus or minus the  $ME_{95}$ ),  $t^*$  is the two-tailed  $t$ -value found in the students  $t$ -table,  $\sigma$  is the standard deviation from the mean for the mean distance from the AIS points to LCP segments, and  $n$  is the sample size.  $ME_{95}$  was calculated for the Hudson Bay and CAA regions separately to enable an assessment of the ability of the LCP algorithm to resolve voyage segments in the more open water Hudson Bay area ( $n = 598$ ) compared with the more channelized CAA ( $n = 327$ ).

Upon employing this methodology, voyages can be reconstructed to an accuracy of  $10.42 \pm 0.67$  km within the NORDREG zone as a whole. Subsequently, an error estimate was constructed for Hudson Bay ( $13.78 \pm 1.99$  km), and the NORDREG zone excluding Hudson Bay ( $8.77 \pm 0.91$  km) (Table 3.4). This indicates that we are 95% confident the actual route that vessels took fell within a distance of  $\sim 8$  to  $14 \pm 2$  km of the LCP generated route (Table 3.4). Given that the error estimates fall within the 25 km x 25 km grid surface generated for subsequent ship analysis, we can be very confident that the true voyage falls within the grid cell that the LCP track is in (*see* Figure 3.9 for grid output).

*Table 3.3. Error estimate for voyage track accuracy compared to AIS points, 2010.*

<b>Region</b>	<b>Mean Displacement (km)</b>
NORDREG zone	10.42 ± 0.67
Hudson Bay	13.78 ± 1.99
NORDREG zone (excluding Hudson Bay)	8.77 ± 0.91

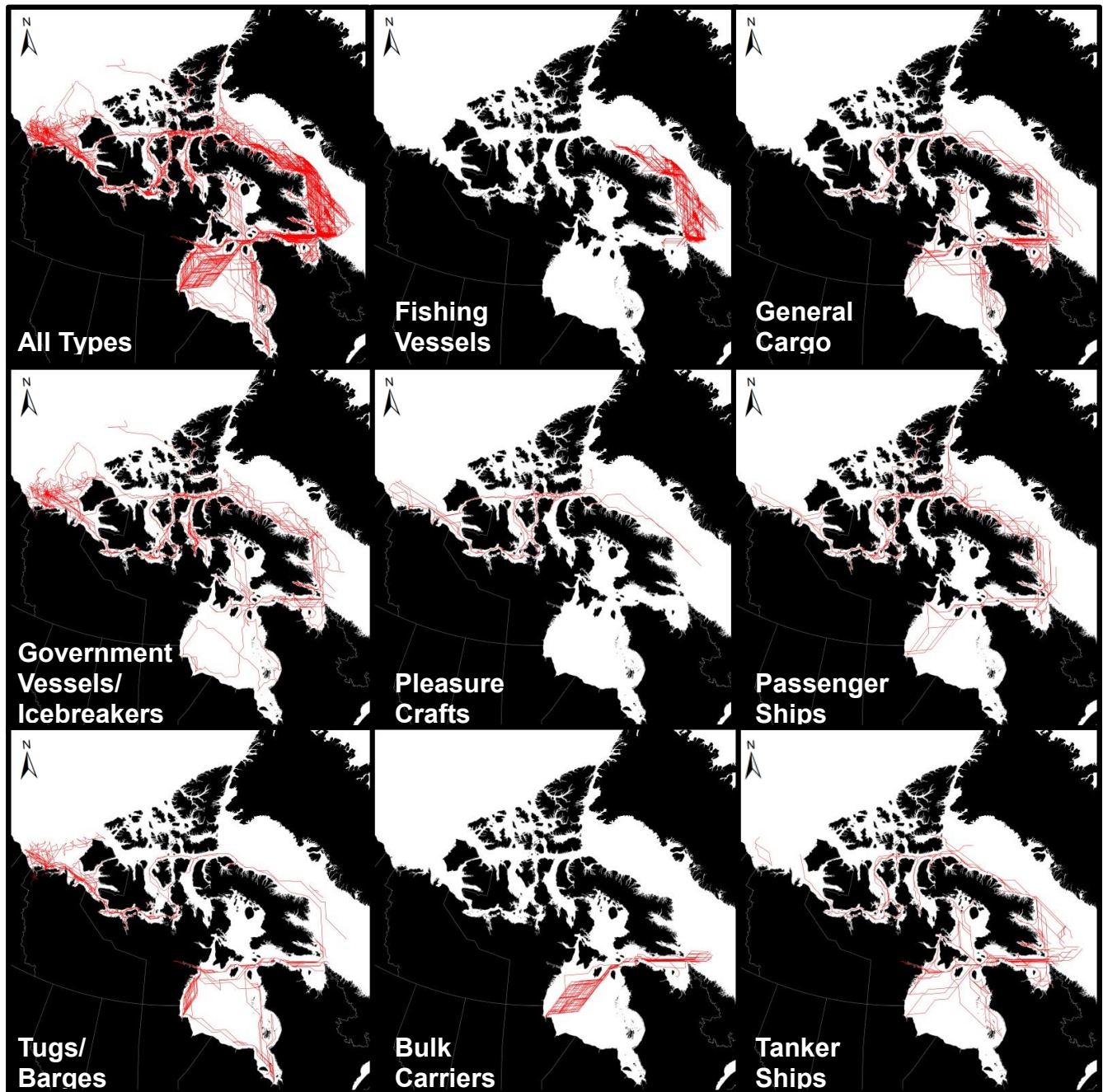
### **3.7 Results**

The LCP algorithm was able to successfully solve 4217 unique voyage segments for 2010, representing 286 unique voyages within the study area of the 288 voyages that contained at least two points. The two voyages that were unable to be resolved are a result of the vessel reporting their location to NORDREG but not moving from their initial reported position, meaning that no segment could be reconstructed. This method improves upon existing methods to connect known ship points, which use a straight line approach to connect points with a line which resulted in their reconstructed vessel tracks going over land. For example, in the study of Halpern et al. (2008) they employed a straight line approach for ship track reconstruction globally, and then had to subsequently exclude any vessel track that went over land. However, in the Canadian Arctic this method would eliminate many ship voyages and their associated tracks due to the abundance of islands and channels.

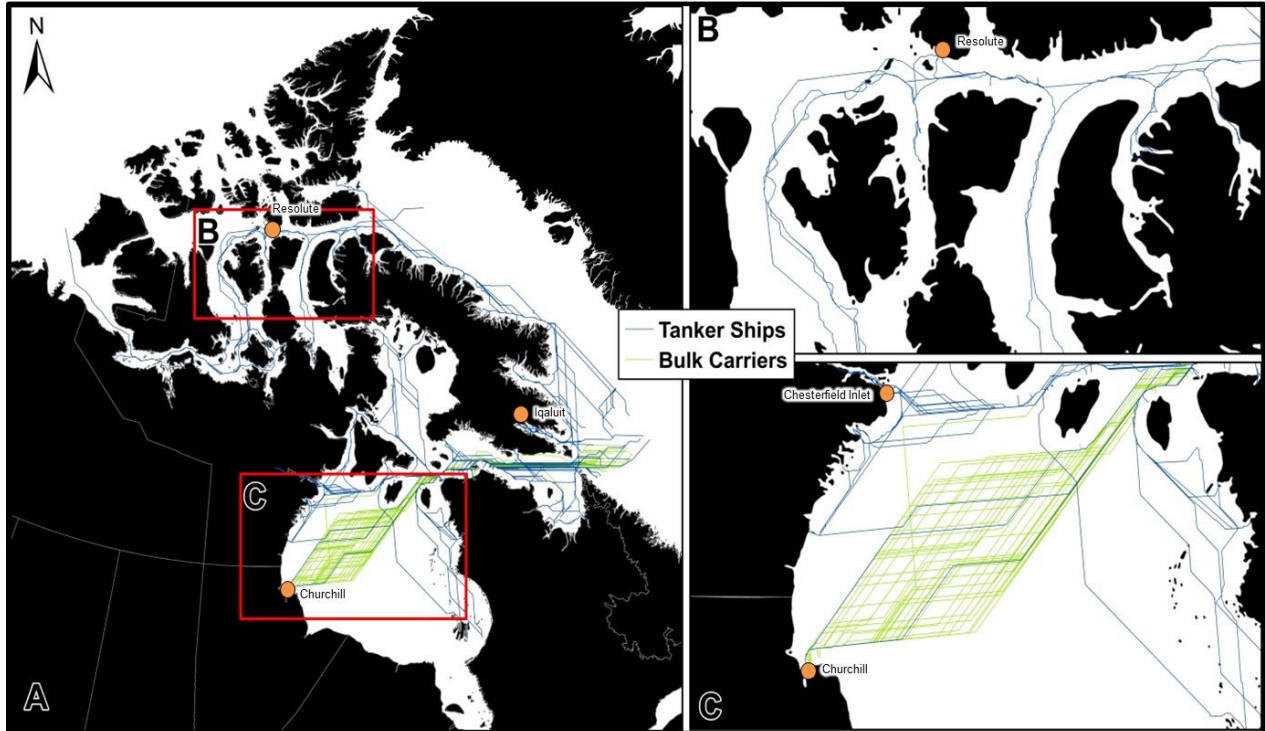
**Table 3.4.** Summary of LCP statistics by vessel type for 2010.

<b>Vessel Type</b>	<b>Number of LCP generated Voyage Segments</b>	<b>Total Segment Length (x 10<sup>4</sup> km)</b>
Bulk Carriers	170	8.5
Fishing Vessels	1425	8.3
General Cargo	387	16.7
Government Vessels and Icebreakers	878	15.7
Passenger Ships	290	9.3
Pleasure Crafts	129	3.5
Tanker Ships	278	11.1
Tug/Barge	660	13.7
<b>All Vessel Types</b>	<b>4217</b>	<b>87.0</b>

Upon solving the LCP voyage segments, statistics can be constructed for vessel voyages in 2010 across the entire NORDREG zone. Collectively, General Cargo vessels traversed the longest distance ( $16.7 \times 10^4$  km), followed by Government Vessels and Icebreakers ( $16.7 \times 10^4$  km) and Tug/Barges ( $13.7 \times 10^4$  km) (Table 3.3). Overall, the least distance travelled within the NORDREG zone was by Pleasure Crafts ( $3.5 \times 10^4$  km), followed by Bulk Carriers and Fishing Vessels ( $\sim 8.4 \times 10^4$  km), and Passenger Ships ( $9.3 \times 10^4$  km) (Table 3.3).

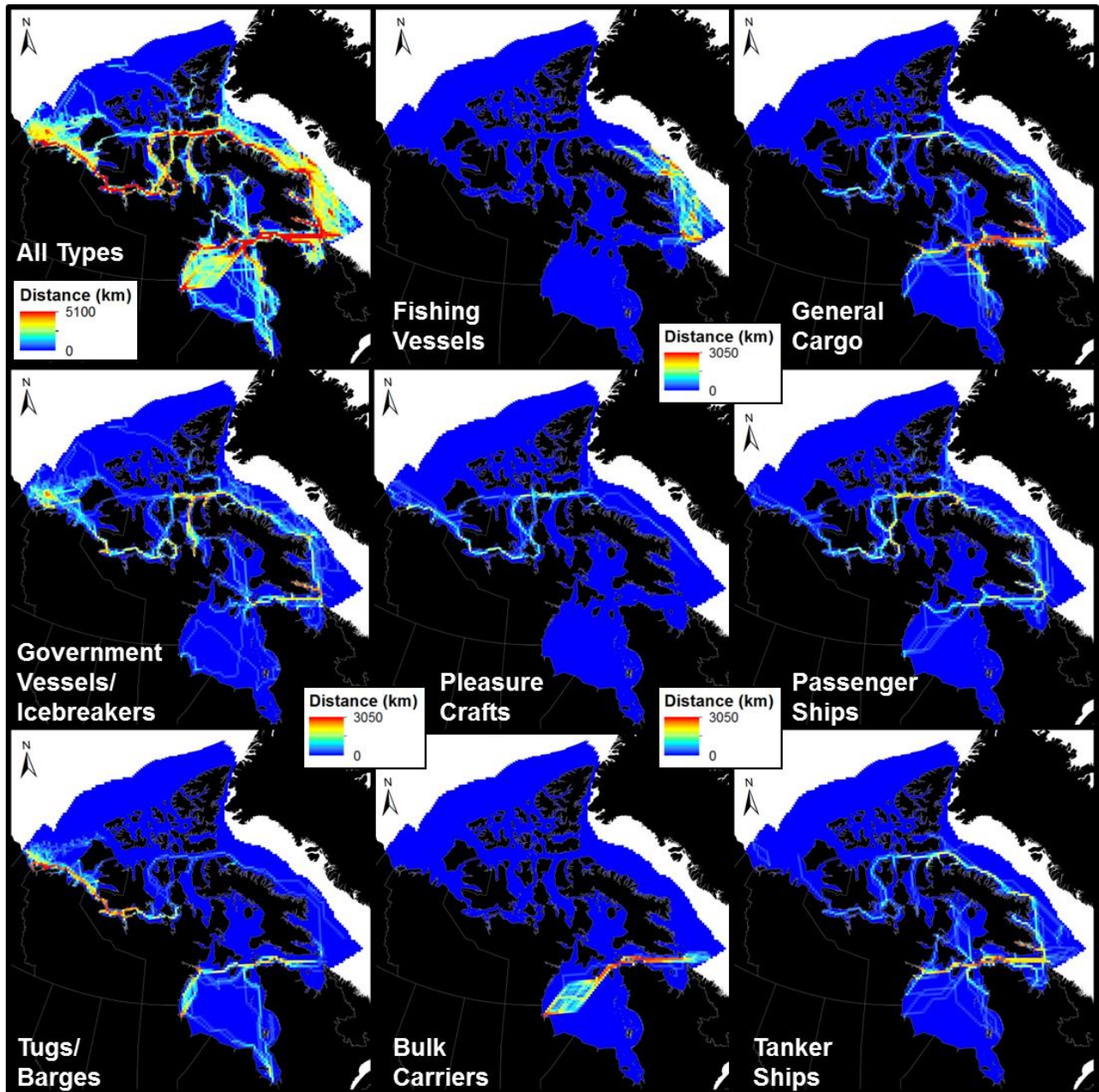


*Figure 3.7. LCP voyage tracks by vessel type in the NORDREG zone, 2010.*



**Figure 3.8.** Bulk Carrier and Tanker Ship vessel tracks for (a) 2010, with a close-up of LCP predicted voyage tracks in (b) the central CAA and (c) Hudson Bay.

Spatially, the distribution of shipping activity indicated by LCP generated vessel tracks varied by vessel type (Figure 3.7). As expected, Bulk Carrier shipping activity was concentrated on the Arctic Bridge shipping route through Hudson Strait and to the port of Churchill, through Hudson Bay. To illustrate the resolution of the voyage tracks in this region, the Bulk Carrier vessel tracks in Hudson Bay (Figure 3.8C) can be compared with the Tanker Ship tracks in the central CAA (Figure 3.8B). In this comparison, the Bulk Carrier tracks are much more dispersed, likely a result of the CAA being more channelized. Furthermore, we see General Cargo vessels, Tanker Ships and Tugs/Barges servicing the needs of communities throughout the Canadian Arctic, and exporting goods out of the Port of Churchill (e.g., Figure 3.7 and 3.8).



*Figure 3.9. Sum of total distance travelled (km) within each grid cell (25 km x 25 km) by vessel type, 2010.*

### ***3.8 Discussion***

Using the LCP generated voyage tracks; we are able to create shipping activity maps by taking the sum of all voyage segments within each 25 km x 25 km grid cell to provide the total distance travelled by all vessels or specific vessel types within that cell (Figure 3.9). Given our confidence in the LCP results, we are able to use the sum of the distance travelled (km) within each cell as a metric for establishing shipping activity regionally over the NORDREG zone (Figure 3.9). We are further able to identify commonly travelled routes for the year 2010 by vessel type within the Canadian Arctic domain through the use of the LCP approach described in Figures 3.3 through 3.6, following the prescribed costs to safe transit identified in Table 3.2

For 2010, regions of intensified shipping activity occurred along the southern NWP route via Eastern Parry Channel then southwards along the eastern coast of Prince of Wales Island and southern coast of Victoria and Banks Islands, in the eastern Arctic within the Baffin Bay/Davis Strait region, and through Hudson Strait into Hudson Bay (Figure 3.9, All Types). Interestingly, Fishing Vessels are constrained to the Baffin Bay/Davis Strait region, while Bulk Carriers travel exclusively to and from the Port of Churchill (Figure 3.9). The activities of all other vessel types (i.e., General Cargo, Government Vessels/Icebreakers, Pleasure Crafts, Passenger Ships, Tugs/Barges, and Tanker Ships) are more dispersed throughout the NORDREG zone (Figures 3.7 and 3.9). Moreover, we can identify “Hot spots” of activity such as the Hudson Strait (i.e., 17.4% of all shipping activity in 2010), as well as along the southern NWP route (i.e., 13.1% of all shipping activity in 2010). Additionally, for 2010, the percentage of total shipping occurring

on a monthly basis for July, August, September, and October, is 13.6%, 35.3%, 29.6%, and 16.5% respectively..

One major challenge with using the LCP approach in this study is that often the initial reporting record falls within the NORDREG zone, meaning that shipping activity along the margins of the NORDREG zone is potentially underestimated. Additionally, LCP segment generation within the open water of Hudson Bay performs less well than the channels of the CAA as demonstrated in Figures 3.7 and Table 3.3. Despite these challenges, the proposed LCP approach improves on existing methods by eliminating the issue of vessels traversing land, which is present in other studies exploring marine traffic which use a straight line approach (e.g., Halpern et al., 2008). Furthermore, the CISDA and NORDREG archives are both available for the entire period since 1990, which provides confidence that this approach can be employed historically, and updated on an on-going basis in the future to ensure longevity of the dataset for future use.

### ***3.9 Conclusions***

This study demonstrates the ability of a LCP approach to successfully reconstruct Arctic shipping routes throughout the Canadian Arctic using total ice concentration, bathymetry, and distance from land, as cost surfaces to safe vessel transit. Using 2010 as a case study, we establish that reconstructed voyage tracks across the Canadian Arctic from daily NORDREG data are accurate to between 8.77 and 13.78 km  $\pm$  1.99 km of their true route when compared with the independent AIS ship archive (Table 3.4). This provides confidence that reconstructed LCP voyages can be sampled to the NSIDC 25 km EASE grid to create a gridded product of

observed annual shipping activity across the Canadian Arctic. In future studies, this product will provide a framework for trend and correlation analysis for all of years of the NORDREG archive from 1990 to present.

## CHAPTER 4: Conclusions

Over the period 1990 to 2012, significant increases in vessel counts were observed for some vessel types (e.g., Government Vessels and Icebreakers, Pleasure Crafts, and Passenger Ships) on monthly and annual time scales coincident with declines in total, MYI, and FYI over the same time period. Significantly, shipping activity experienced modest increases annually at rates between 3 and 8 vessels decade<sup>-1</sup>, the largest overall increases occurred early in the shipping season (June and July at 9 and 22 vessels decade<sup>-1</sup> respectively), and at the conclusion of the shipping season in November at 13 vessels decade<sup>-1</sup>. This was coincident with the extension of the melt season length in the spring and fall. However, only weak correlations exist between declines in shipping activity and changing sea ice conditions, suggesting that there are likely other factors influencing changing shipping activity in the Canadian North (e.g., Brigham, 2011). This work confirmed that in recent years ship traffic in some regions of the Arctic has increased independently of sea ice decline.

Following temporal analysis of shipping activity and physical environmental changes over the NORDREG zone, a LCP approach was employed to reconstruct historical voyage tracks to better understand the spatial variability of shipping activity in Canada. The LCP approach was employed for the year 2010 across the entire NORDREG domain through the integration of 3 datasets: the NORDREG ship archive, CISDA weekly regional ice charts, and the ETOPO2v2 bathymetric dataset. Error analysis comparing reconstructed routes and the independent AIS ship archive revealed that the LCP approach is suitable for reconstructing historical ship traffic to an accuracy of between  $8.77 \pm 0.91$  km for the NORDREG zone excluding Hudson Bay, and 13.78

$\pm 1.99$  km for Hudson Bay (Table 3.4). This exercise provides confidence that a gridded 25 km shipping activity product generated from LCP reconstructed voyage segments on an annual basis would be suitable for all years of data within the NORDREG ship archive.

#### ***4.1 Contributions***

The NORDREG ship archive, CISDA weekly regional ice charts, NCEP-NCAR reanalysis, satellite derived MSL data product, and AIS ship archive provide the ability to: 1) obtain a holistic understanding of trends and correlations between the physical environment and Canadian Arctic shipping activity through investigations of changes in the sea ice regime, MSL, and SAT, 2) obtain a baseline understanding of temporal shipping trends by vessel type over the period 1990 to 2012 on monthly, annual, and shipping season time scales, and 3) reconstruct historical shipping activity using a LCP approach. Significantly, Chapters 2 and 3 collectively use observational data to quantify the relationships between the changing Arctic environment (e.g., sea ice conditions, SAT, and MSL) and Arctic marine transportation activities in Canada.

Temporal analysis of sea ice area over the NORDREG zone revealed significant declines of total, MYI, and FYI area in agreement with current model simulations and observational studies (e.g. Stephenson et al., 2013, 2011; Sou and Flato, 2009; Tivy et al., 2011a). With the reported declines of MYI area across the NORDREG zone dominating over FYI declines on the shipping season (June 25 to October 15) and monthly time scales, this provides confirmation that the older, thicker sea ice regime in the Canadian Arctic is being replaced by a more seasonal FYI regime consistent with the findings of Maslanik et al. (2011) and Tivy et al. (2011a).

Additionally, the delay in freeze onset over the 1990 to 2012 time period combined with increasing SAT trends, and MYI declines dominating in the fall and winter months, suggest there is a possibility of an extension of the shipping season later into the fall (*see* Chapter 2). Particularly, the extension of the melt season length within the NORDREG zone (1990 to 2012) of 11 days decade<sup>-1</sup>, largely dominated by later freeze up by 8 days decade<sup>-1</sup>, is greater compared to pan-Arctic domain changes to the melt season length reported by Stroeve et al. (2014) of 5 days decade<sup>-1</sup> from 1979 to 2013, and by Tivy et al. (2011a) of 7 days decade<sup>-1</sup> from 1979 to 2008 in the CAA. This has implications for future route planning, and resource allocation (e.g. fuelling services, search and rescue capability), which may need to increase later in the shipping season to service potential increases in shipping brought on by these changes of the physical environment. Specific vessel types are experiencing the greatest increases in shipping traffic across the Canadian Arctic region including Passenger Ships, Pleasure Crafts, and Bulk Carriers consistent with increases reported by earlier studies including Dawson et al. (2007, 2014), Stewart et al. (2010), Lasserre and Têtu (2015), Hodgson et al. (2013), and the Arctic Council (2009). This study builds upon the aforementioned studies through the generation of a long time series (1990-2012) of all vessel types operating within the Canadian Arctic using the NORDREG ship archive, which has not previously been undertaken on such a long time scale using observational data.

Significantly, previous knowledge about the spatial distribution of Arctic maritime activity has been based on data recorded over short periods, such as in the Arctic Marine Shipping Assessment (AMSA) for the year 2004 (e.g. Arctic Council, 2009), or through the use of model simulations (e.g. Smith and Stephenson, 2013). However, a long-term observational spatio-

temporal time series of historic Arctic shipping activity in Canada does not exist. Through the reconstruction of historical vessel tracks using a LCP approach, we are able to convert a point dataset (individual reported points from the NORDREG ship archive) into a line dataset (voyage tracks) and as a result can provide a methodology to fill this knowledge gap. Through identifying where ships have historically travelled throughout the Canadian Arctic, this provides a first step in better understanding interactions and implications that changing shipping activity may have on the environment, people, the economy, resource development projects, and wildlife.

#### ***4.2 Limitations***

The NORDREG ship archive provides a comprehensive record of Arctic shipping activity within Canada, despite the fact that reporting still remains voluntary for vessels under 300 gross tons and not carrying dangerous goods (CCG, 2013). However, it is likely that most small vessels report to NORDREG even when they are not obligated to do so, due to the advantages it provides such ice information services and enhanced search and rescue response (Rompkey and Cochrane, 2008). As a result, the dataset likely captures most shipping activity (~98%) in the Canadian Arctic, particularly for larger vessels (Rompkey and Cochrane, 2008). To fill any future gaps in the NORDREG record, it will be possible to integrate external data sources such as the AIS ship archive. The AIS record is becoming an increasingly valuable dataset, as revisit times for the exactEarth AIS data product will reduce significantly with the expected launch of two new satellites in 2015 (to bring their total number of satellites to 9), which is expected to reduce revisit time to one hour in early 2016 (exactEarth, 2015).

An additional potential limitation is that the term voyage, as used in the NORDREG ship archive to refer to the entry and exit of a vessel in/out of the NORDREG zone, is likely not the most appropriate metric for determining changing ship activity. This is because a ship that spends the entire shipping season moving within the NORDREG zone would only be counted as one voyage, whereas a vessel that enters and exists multiple times but only stays along the margin of the NORDREG zone for a day at a time would be counted as multiple voyages, even though the actual time and distance travelled within the zone is significantly less. An alternative metric such as time or total length travelled in km, or time spent in the NORDREG zone, would likely be more appropriate moving forward as this would more accurately capture the amount of shipping activity a vessel undertakes within the NORDREG zone. The NORDREG ship archive is also missing a time field, with positions only reported to the nearest day, which can produce ambiguity in the vessel record (and therefore problematic inputs into the LCP approach) when there are multiple reported points on the same day.

With respect to the CISDA, the ice charts are currently available on a weekly basis since 2011, but prior to this they were only issued monthly in the winter months until March 2006, at which point their availability was increased to bi-weekly (CIS, 2007). This poses some challenges with their use in LCP analysis as ice charts used in the LCP reconstruction may not be from the date of ice chart being issued, but from a period within +/- 1 week of the reported date of the initial reported ship point.

### ***4.3 Future Work***

This study established that a LCP approach is suitable for reconstruction of historical shipping routes in the Canadian Arctic from sparse point records of ship locations. Future analysis will enable reconstruction of historical shipping routes on an annual basis from 1990 to present following the LCP approach described in *Chapter 3* based on data on sea ice, bathymetry and distance from coastline. This will provide a comprehensive understanding of historical shipping activity, which in turn will enable prediction of how maritime activity within the Canadian Arctic will evolve in the future. Furthermore, the dataset can be subset by characteristics such as vessel type and tonnage to explore vessel specific patterns to better understand maritime use within the North.

Significantly, upon extending the spatial ship track time series to the years 1990 to 2014 using the LCP approach as described in *Chapter 3*, we will be able to use these ship tracks to explore a variety of different aspects of Arctic Shipping activity. This includes potential investigations of greenhouse gas emissions from ships and its variability through time, based on the number of vessels and the time they spend in the Arctic. Another aspect that could be studied is the number of people (crew, passengers) and their locations within the Arctic that a) arrive by/on a ship, or b) transit through the Arctic by ship, to provide informed decisions on search and rescue planning and costly infrastructure allocation to support the needs of Arctic marine vessels (DFO, 2015). Furthermore, understanding of the historical distribution of Arctic maritime activities can help inform search and rescue policy to help improve upon the challenging logistics of emergency response in the Arctic. Additionally, we can start to explore how economics may also

drive changes to shipping routes within the Arctic based on known locations of mines and other resource exploration projects.

Future analysis can act as a tool to help answer important policy questions aimed at minimizing the environmental and socio-economic risks of Arctic shipping activities in Canada. Importantly, trend maps generated using the gridded 25 km product expanded to the 1990 to 2014 time period can contribute to current federal initiatives within Transport Canada to establish ‘strategic shipping corridors’ aimed at minimizing risks posed by sea ice and other navigational hazards, while limiting the potential environmental impacts of shipping. To conclude, this study contributes to two research opportunities outlined in the 2009 AMSA report: 1) the development of a consistent and accurate circumpolar database of Arctic ship activity, and 2) trend analysis of shipping activity (Arctic Council, 2009, p. 94). There are also dozens of other possibilities available with the analysis of datasets of this type, including improved forecasting of future shipping routes, and planning of future infrastructure development projects based on observed and projected shipping activity in Canada’s North.

## CHAPTER 5: References

- Agnew T, Howell S (2003). The use of operational ice charts for evaluating passive microwave ice concentration data, *Atmos. Ocean* 41, 317–331. doi:10.3137/ao.410405.
- Arctic Council (2009). Arctic Marine Shipping Assessment Report, April 2009, second printing.
- Bekryaev RV, Polyakov IV, Alexeev VA (2010). Role of polar amplification in long-term surface air temperature variations and modern Arctic warming. *J. Climate* 23(14):3888-3906.
- Bourke RH, Garrett RP (1987). Sea ice thickness distribution in the Arctic Ocean, *Cold Reg. Sci. Technol.*, 13, 259– 280.
- Brigham, LW (2007). Thinking about the Arctic’s future: Scenarios for 2040. *Futurist*, 41(5), 27–34.
- Brigham L (2011). Marine protection in the Arctic cannot wait. *Nature*, 478(7368):157. doi: 10.1038/478157a.
- Canadian Coast Guard, CCG (2012). Ice Navigation in Canadian Waters. Ottawa.
- Canadian Coast Guard, CCG (2013). Vessel Traffic Reporting Arctic Canada Traffic Zone (NORDREG). Online: [http://www.ccg-gcc.gc.ca/eng/MCTS/Vtr\\_Arctic\\_Canada](http://www.ccg-gcc.gc.ca/eng/MCTS/Vtr_Arctic_Canada).
- Canadian Coast Guard. Department of Fisheries and Oceans: Government of Canada, CCG-DFO (2015). Annual edition April 2015 to March 2016 – notices to mariners 1 to 46: 27c under keel clearance table. Retrieved from website: <http://www.notmar.gc.ca/eng/services/annual/section-c/notice-27c.pdf>.
- Canadian Ice Service, CIS (2007). Regional charts: History, accuracy, and caveats, Archive Documentation Series 1, Ottawa. Online: [http://ice.ec.gc.ca/IA\\_DOC/cisads\\_no\\_001\\_e.pdf](http://ice.ec.gc.ca/IA_DOC/cisads_no_001_e.pdf).
- Canadian Ice Service, CIS (2011). Sea Ice Climatic Atlas: Northern Canadian Waters 1981–2010, Ottawa.
- Chircop A (2009). The growth of international shipping in the arctic: Is a regulatory review timely?. *The International Journal of Marine and Coastal Law*, 24, 355-380.
- Comiso, JC (2012). Large Decadal Decline of Arctic Multiyear Ice Cover. *J. Climate* 25, 1176-1193. doi: 10.1175/JCLI-D-11-00113.1.
- Dawson J, Johnston ME, Stewart EJ (2014). Governance of Arctic expedition cruise ships in a time of rapid environmental and economic change. *Ocean & Coastal Management*, 89, 88–99. doi:10.1016/j.ocecoaman.2013.12.005.

- Dawson J, Maher P, Slocombe SD (2007). Climate change, marine tourism and sustainability in the Canadian Arctic: contributions from systems and complexity approaches. *Tourism in Marine Environments*. 4(2/3), 69-83.
- Department of Fisheries and Oceans: Government of Canada, DFO (2015). Enhancing the Arctic Search and Rescue Capacity. Retrieved August 13, 2015, from <http://news.gc.ca/web/article-en.do?nid=1009409>.
- Derksen C, Smith SL, Sharp M, Brown L, Howell S, Copland L and 14 others (2012). Variability and change in the Canadian Cryosphere. *Climatic Change* 115(1), 59-88.
- exactEarth (2015). Satellite AIS Just Got Real. Retrieved July 24, 2015, from <http://blog.exactearth.com/blog/satellite-ais-just-got-real>.
- Guy E (2006). Evaluating the viability of commercial shipping in the Northwest Passage. *Journal of Ocean Technology*, 1(1), 9–18.
- Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C and 13 others (2008). A Global Map of Human Impact on Marine Ecosystems. *Sci.*, 318(5865).doi: 10.1126/science.1149345.
- Hochheim KP, Barber DG (2014). An Update on the Ice Climatology of the Hudson Bay System An Update on the Ice Climatology of the Hudson Bay System. *Arct. Antarct. Alp. Res.*, 46(1), 66–83..
- Hodgson, JRF, Russell, WD, Megganety, M (2013). Exploring Plausible Futures for Marine Transportation in the Canadian Arctic: A Scenarios' Based Approach. A report prepared for Transport Canada.
- Hollander M, Wolfe DA (1973). *Nonparametric Statistical Methods*. Toronto, ON: John Wiley & Sons, Inc.
- Howell SEL, Yackel JJ (2004). A vessel transit assessment of sea ice variability in the Western Arctic, 1969–2002: implications for ship navigation. *Canadian Journal of Remote Sensing*, 30(2), 205–215. doi:10.5589/m03-062.
- Howell SEL, Derksen C, Pizzolato L, Brady M (2015). Multiyear ice replenishment in the Canadian Arctic Archipelago: 1997–2013, *J. Geophys. Res.: Oceans*, 120, 1623–1637, doi:10.1002/2015JC010696.
- Howell SEL, Duguay CR, Markus T (2009). Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979–2008. *Geophys. Res. Lett.*, 36, L10502. doi:10.1029/2009GL037681.
- Howell SEL, Wohleben T, Dabboor M, Derksen C, Komarov A, Pizzolato L (2013a). Recent changes in the exchange of sea ice between the Arctic Ocean and the Canadian Arctic Archipelago. *J. Geophys. Res.: Oceans*, 118. doi: 10.1002/jgrc.20265.

- Howell SEL, Wohlleben T, Komarov A, Pizzolato L, Derksen C (2013b). Recent extreme light sea ice years in the Canadian Arctic Archipelago: 2011 and 2012 eclipse 1998 and 2007. *The Cryosphere*, 7(6), 1753–1768. doi:10.5194/tc-7-1753-2013.
- International Maritime Organization, IMO (2010). Guidelines for ships operating in polar waters, 2010 edition. Online:  
<http://www.imo.org/Publications/Documents/Attachments/Pages%2520from%2520E190E.pdf>.
- International Maritime Organization, IMO (2014). Shipping in polar waters: Development of an international code of safety for ships operating in polar waters (Polar Code). Retrieved May 12, 2014, from  
<http://www.imo.org/MediaCentre/HotTopics/polar/Pages/default.aspx>.
- Inuit Circumpolar Council, ICC (2008). The sea ice is our highway: An Inuit perspective on transportation in the Arctic. Retrieved from  
[http://inuitcircumpolar.com/files/uploads/iccfiles/20080423\\_iccamsa\\_finalpdfprint.pdf](http://inuitcircumpolar.com/files/uploads/iccfiles/20080423_iccamsa_finalpdfprint.pdf).
- Jeffries MO, Overland JE, Perovich DK (2013). The Arctic shifts to a new normal, *Phys. Today*, 66(10), 35–40, doi:10.1063/PT.3.2147.
- Joly S, Senneville S, Caya D, Saucier FJ (2011). Sensitivity of Hudson Bay Sea ice and ocean climate to atmospheric temperature forcing. *Clim. Dynam.* 36: 1835-1849.
- Khon VC, Mokhov II, Latif M, Semenov VA, Park W (2009). Perspectives of Northern Sea Route and Northwest Passage in the twenty-first century. *Climatic Change*, 100(3-4), 757–768. doi:10.1007/s10584-009-9683-2.
- Kistler R, Kalnay E, Collins W, Saha S, White G, Woollen J and 7 others (2001). The NCEP–NCAR 50-year reanalysis: Monthly means CD-ROM and documentation. *Bull. Am. Meteorol. Soc.*, 82, 247–267.
- Kubat I, Collins A, Timco G (2007). Year-round shipping in the Canadian arctic: ice conditions and regulatory requirements. Retrieved April 2, 2014 from <http://nparc.cisti-icist.nrc-cnrc.gc.ca/npsi/ctrl?action=rtdoc&an=12327360&lang=en>.
- Kwok R (2006). Exchange of sea ice between the Arctic Ocean and the Canadian Arctic Archipelago. *Geophys. Res. Lett.*, 33(16), L16501. doi:10.1029/2006GL027094.
- Lasserre F, Pelletier S (2011). Polar super seaways? Maritime transport in the Arctic: an analysis of shipowners' intentions. *J. Transp. Geogr.*, 19, 1465-1473. doi: 10.1016/j.jtrangeo.2011.08.006.
- Lasserre F, Têtu PL (2015). The cruise tourism industry in the Canadian Arctic: analysis of activities and perceptions of cruise ship operators. *Polar Record*, 51, pp 24-38. doi:10.1017/S0032247413000508.

- Laxon SW, Giles KA, Ridout AL, Wingham DJ, Willatt R, Cullen R, ... Davidson M (2013). CryoSat-2 estimates of Arctic sea ice thickness and volume, *Geophys. Res. Lett.*, 40, 732–737, doi:10.1002/grl.50193.
- Liu, M and Kronbak, J (2010). The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. *J. Transp. Geogr.*, 18, 434 – 444, doi: 10.1016/j.trangeo.200908.004.
- Markus T, Stroeve JC, Miller J (2009). Recent changes in Arctic sea ice melt onset, freezeup, and melt season length. *J. Geophys. Res.*, 114, C12024. doi:10.1029/2009JC005436.
- Maslanik J, Stroeve J, Fowler C , Emery W (2011). Distribution and trends in Arctic sea ice age through spring 2011, *Geophys. Res. Lett.*, 38, L13502. doi:10.1029/2011GL047735.
- Maslanik J, Stroeve J, Fowler C, Emery W (2011). Distribution and trends in Arctic sea ice age through spring 2011. *Geophys. Res. Lett.*, 38(13). doi:10.1029/2011GL047735.
- Massonnet F, Fichet T, Goosse H, Bitz CM, Philippon-Berthier G, Holland M, Barriat PY (2012). Constraining projections of summer Arctic sea ice. *The Cryosphere*, 6, 1383-1394. doi: 10.5194/tc-6-1383-2012.
- Melling, H (2002). Sea Ice of the Northern Canadian Arctic Archipelago. *J. Geophys. Res.*, 107,C11,3181. doi:10.1029/2001JC001102.
- Parkinson CL (2014). Spatially mapped reductions in the length of the Arctic sea ice season, *Geophys. Res. Lett.*, 41, 4316–4322, doi:10.1002/2014GL060434.
- Pistone K, Eisenman I, Ramanathan V (2014). Observational determination of albedo decrease caused by vanishing Arctic sea ice. *P. Natl. Acad. Sci.*, 1–5. doi:10.1073/pnas.1318201111.
- Pizzolato L, Howell SEL, Derksen C, Dawson J, Copland L (2014). Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. *Climatic Change*. doi: 10.1007/s10584-013-1038-3.
- Prowse TD, Furgal C, Chouinard R, Melling H, Mildurn D, Smith S (2009). Implications of Climate Change for Economic Development in Northern Canada: Energy, Resource, and Transportation Sectors. *AMBIO*, 38(5), 272-281.
- Rodionov SN (2004). A sequential algorithm for testing climate regime shifts. *Geophys. Res. Lett.*, 31, L09204. doi:10.1029/2004GL019448.
- Rogers TS, Walsh JE, Rupp TS, Brigham LW, Sfraga M (2013). Future Arctic marine access: analysis and evaluation of observations, models, and projections of sea ice. *The Cryosphere*, 7(1), 321–332. doi:10.5194/tc-7-321-2013.

- Rompkey W, Cochrane E (2008). The Coast Guard in Canada's Arctic: Interim Report. Senate of Canada, Standing Senate and Committee on Fisheries and Oceans. Fourth Report. Online: <http://www.parl.gc.ca/Content/SEN/Committee/392/fish/rep/rep04jun08-e.pdf>.
- Samra B, Randles, RH (1988). A test for correlation based on Kendall's Tau. *Commun. Stat. Theory Methods* 17(9), 3191-3205.
- Schoyen H, Brathen S (2011). The Northern Sea Route versus the Suez Canal: Cases from bulk shipping. *J. Transp. Geogr.*, 19(4):977–983, doi: 10.1016/j.jtrangeo.2011.03.003.
- Serreze MC, Holland MM, Stroeve J (2007). Perspectives on the Arctic's shrinking sea-ice cover. *Sci.*, 315(5818), 1533-1536. doi:10.1126/science.1139426.
- Smith LC, Stephenson SR (2013). New Trans-Arctic shipping routes navigable by midcentury. *P. Natl. Acad. Sci.* doi: 10.1073/pnas.1214212110.
- Somanathan S, Flynn CP, Szymanski KJ (2007). Feasibility of a Sea Route through the Canadian Arctic. *Maritime Economics and Logistics* 9, 324–334. doi: doi:10.1057/palgrave.mel.9100185.
- Sou T, Flato G (2009). Sea Ice in the Canadian Arctic Archipelago: Modeling the Past (1950–2004) and the Future (2041–60). *J. Climate* 22, 2181 – 2198. doi: 10.1175/2008JCLI2335.1.
- Stephenson SR, Smith LC, Agnew JA (2011). Divergent long-term trajectories of human access to the Arctic. *Nat. Clim. Chang.*, 1, 156-160. doi:10.1038/nclimate1120.
- Stephenson SR, Smith LC, Brigham LW, Agnew JA (2013). Projected 21st-century changes to Arctic marine access. *Climatic Change* 118, 885-899. doi: 10.1007/s10584-012-0685-0.
- Stewart EJ, Dawson J, Draper D (2010). Monitoring patterns of cruise tourism across Arctic Canada. In: Luck, M., Maher, P.T., Stewart, E.J. (Eds.), *Cruise Tourism in the Polar Regions: Promoting Environmental and Social Sustainability*. Earthscan Reader, pp. 133-145.
- Stroeve J, Serreze M, Drobot S, Gearheard S, Holland M, Maslanik J, Meier W, Scambos T (2008). Arctic Sea Ice Extent Plummet in 2007. *Eos, Transactions, American Geophysical Union*, 89(2): 13-14. doi:10.1029/2008EO020001.
- Stroeve J, Serreze MC, Holland M, Kay J, Malanik J, Barrett AP (2012). The Arctic's rapidly shrinking sea ice cover: a research synthesis. *Climatic Change*, 110(3-4). doi: 10.1007/s10584-011-0101-1.
- Stroeve JC, Markus T, Boisvert L, Miller J, Barrett A (2014). Changes in Arctic melt season and implications for sea ice loss. *Geophys. Res. Lett.*, 41(4), 1216–1225. doi:10.1002/2013GL058951.

- Tang CL, Ross CK, Yao T, Petrie B, DeTracey BM, Dunlap E (2004). The circulation, water masses and sea-ice of Baffin Bay, *Prog. Oceanogr.*, 63, 183–228, doi:10.1016/j.pocean.2004.09.005.
- Tivy A, Alt B, Howell S, Wilson K, Yackel J (2007). Long-range prediction of the shipping season in Hudson Bay: A statistical approach. *Weather Forecast.*, 22, doi:10.11/WAF1038.1.
- Tivy A, Howell SEL, Alt B, McCourt S, Chagnon R, Crocker G, Carriers T, Yackel JJ (2011a). Trends and variability in summer sea ice cover in the Canadian Arctic based on the Canadian Ice Service Digital Archive. *J. Geophys. Res.: Oceans* 116, C06027. doi:10.1029/2011JC007248.
- Tivy A, Howell SEL, Alt B, Yackel JJ, Carrieres T (2011b). Origins and Levels of Seasonal Forecast Skill for Sea Ice in Hudson Bay Using Canonical Correlation Analysis. *J. Climate*, 24(5), 1378–1395. doi:10.1175/2010JCLI3527.1.
- Transport Canada, TC (2007). Automatic Identification System (AIS) Requirement - July 1, 2008. (RDIMS No. 2481055). Ottawa, ON: Transport Canada, Safety and Security. Retrieved July 23, 2015, from <http://www.tc.gc.ca/eng/marinesafety/bulletins-2007-09-eng.htm>.
- U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center, NGDC (2006). 2-minute Gridded Global Relief Data (ETOPO2v2) <http://www.ngdc.noaa.gov/mgg/fliers/06mgg01.html>.
- Wang M, Overland JE (2012). A sea ice free summer Arctic within 30 years: An update from CMIP5 models. *Geophys. Res. Lett.*, 39, L18501. doi:10.1029/2012GL052868.
- Van Wychen, W., D. O. Burgess, L. Gray, L. Copland, M. Sharp, J. A. Dowdeswell, and T. J. Benham (2014). Glacier velocities and dynamic ice discharge from the Queen Elizabeth Islands, Nunavut, Canada, *Geophys. Res. Lett.*, 41, 484–490, doi:10.1002/2013GL058558.
- Zhang J, Lindsay R, Schweiger A, Steele M (2013). The impact of an intense summer cyclone on 2012 Arctic sea ice retreat. *Geophys. Res. Lett.*, 40, 720 – 726. doi: 10.1002/grl.50190.
- Zhang X, Vincent LA, Hogg WD, Niitsoo A (2000). Temperature and precipitation trends in Canada during the 20th century. *Atmos. Ocean* 38(3), 395–429. doi: 0705-5900/2000/0000-0395.