

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

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**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 surface air temperatures (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.

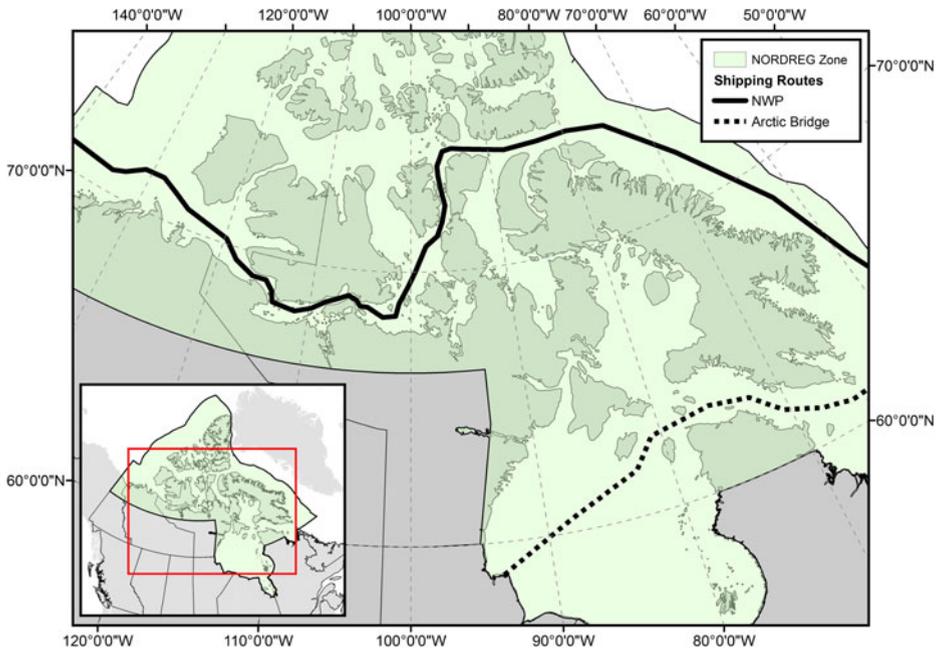
## 1 Introduction

Two major shipping routes extend through Canadian Arctic waters, the Northwest Passage (NWP), and the Arctic Bridge (Fig. 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

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**Fig. 1** Map of the NORDREG zone boundary and Arctic Shipping Routes, derived using the Canadian Coast Guard NORDREG zone, and AMSA Shipping Routes (CCG, 2013; Arctic Council 2009)

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).

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. 2011; 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 and 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  $\text{km}^2$ . 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. 2013). 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 Data description

### 2.1 Vessel (NORDREG) dataset

Within the Vessel Traffic Reporting Arctic Canada Traffic Zone, commonly known as the NORDREG zone (Fig. 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 ten 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 1). 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 zone study area, a total of 82 555 reporting records of 129 603 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 eight 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 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 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

**Table 1** NORDREG Vessel Type Classifications grouped into 10 categories

AMSA classification	Reporting records <sup>a</sup>	Unique vessels <sup>b</sup>	Original classification in the NORDREG dataset
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>a</sup> Total reporting records included in the analysis over the 1990–2012 study period

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

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 seven 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 two to reduce the magnitude of outliers on the detection of regime shifts, as values outside of two standard deviations of the mean are weighted inversely proportional to the distance from the expected mean value of the new regime (Rodionov 2004).

## 2.2 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 (Tivy et al. 2011). 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. (2011) 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 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 retrieved from National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis performed on  $2.5^{\circ} \times 2.5^{\circ}$  grid cells over the NORDREG zone (Kistler et al. 2001).

## 3 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

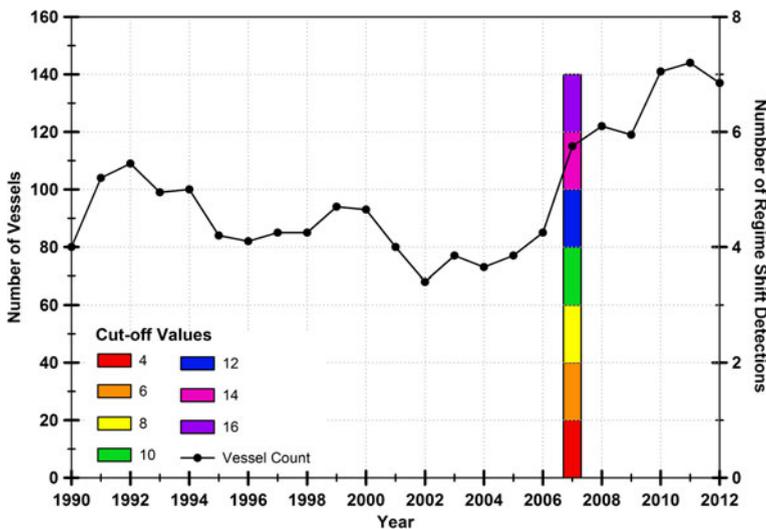
using Kendall's tau rank based correlation. The original time series spans from 1990 to 2012, with each subsequent correlation recalculated through shortening the time series by one year from 1990 to the time period of 2002–2012, while ensuring a minimum of 10 years was used in each analysis (1990–2012, 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).

## 4 Results

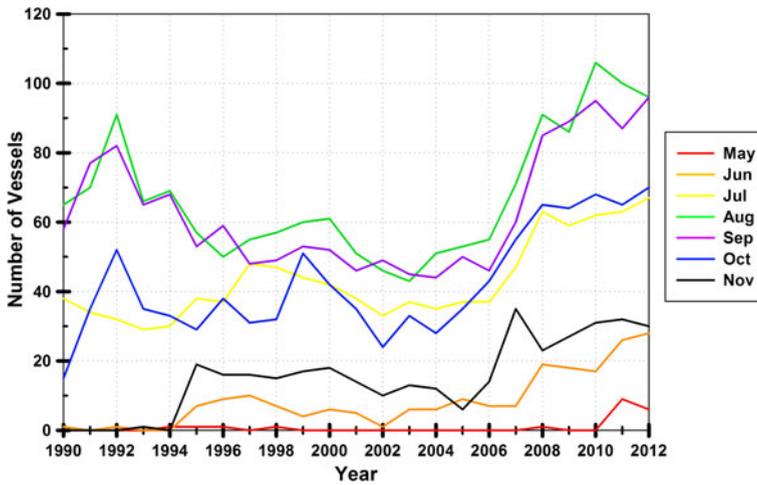
### 4.1 Shipping trends and variability

Arctic marine transportation activities in the NORDREG zone, as characterized by total vessel counts, have seen a sustained increase since 2007 (Fig. 2). Increases in vessel counts in the June to October shipping season were also observed for 2009 through 2011 (Fig. 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). Bulk Carriers and Passenger Ships are also experiencing statistically significant increases of 3 vessels decade<sup>-1</sup> (Table 2).

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). 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).



**Fig. 2** Regime shifts were detected for all cut-off values in 2007; no regime shifts were detected in any other year for total annual vessel counts, 1990–2012. Cut-off values represent the number of years used in regime detection window thresholds



**Fig. 3** Total monthly vessel counts from May through November in the NORDREG zone, 1990–2012

Annually, for total vessel counts, a regime shift was detected in the vessel count time series in 2007 at all of the cut-off values (Fig. 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 (Fig. 2).

**Table 2** Sen’s slope of decadal vessel count trends in the NORDREG zone, 1990–2012

Vessel Type	Trend (Vessels Decade <sup>-1</sup> )												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
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	–	–	–	–	–	0	1	1	1	<b>3</b>	<b>3</b>	–	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	<b>2</b>	<b>3</b>	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	7	0	–	4
Tanker Ships	–	–	–	–	–	<b>2</b>	<b>2</b>	0	6	0	<b>1</b>	0	1

Bold values are significant at the 95 % confidence level or higher

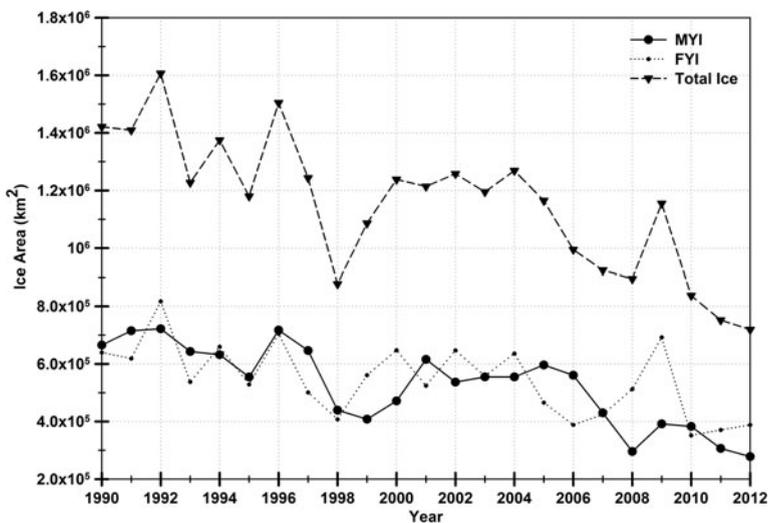
“–” indicates no trend

## 4.2 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 (Fig. 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 to 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 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. 2013). 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 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 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).

## 4.3 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



**Fig. 4** Time series of shipping season mean total ice, MYI, and FYI area ( $\text{km}^2$ ) in the NORDREG zone, 1990–2012

**Table 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

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

Bold values are significant at the 95 % confidence level or higher

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 4). Similarly correlations between monthly mean total ice and MYI area, and monthly vessel counts in the NORDREG zone revealed significant

**Table 4** Kendall’s Tau Correlations for mean monthly sea ice area (km<sup>2</sup>) and monthly vessel counts in the NORDREG zone for July through October, 1990–2012

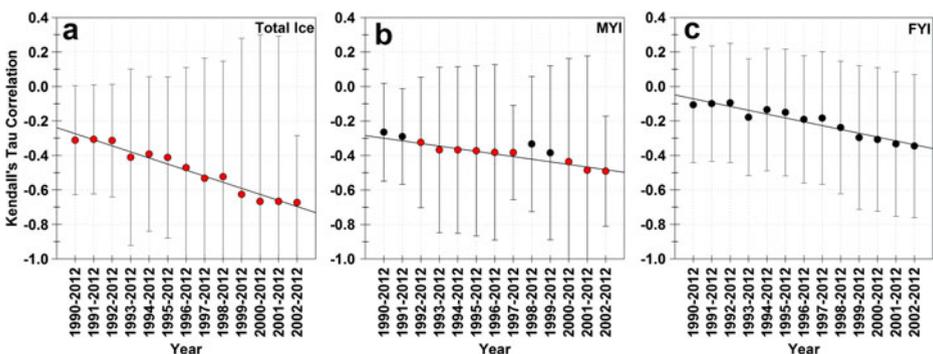
Vessel Type	Ice area									
	Total					MYI				
	Jul	Aug	Sep	Oct	Shipping Season	Jul	Aug	Sep	Oct	Shipping Season
All Vessel Types	-0.22	-0.23	-0.19	0.00	<b>-0.31</b>	<b>-0.32</b>	<b>-0.44</b>	-0.19	-0.15	-0.26
Bulk Carriers	-0.01	-0.04	0.08	<b>0.30</b>	0.04	-0.16	-0.23	-0.02	0.19	-0.07
Fishing Vessels	-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

Bold values are significant at the 95 % confidence level or higher

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 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.

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 (Fig. 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.

Increasing trends in SAT were observed in January, February, and July through October at a rate of  $0.7\text{ }^{\circ}\text{C}$  to  $1.8\text{ }^{\circ}\text{C}$  decade $^{-1}$  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  $0.6\text{ }^{\circ}\text{C}$  decade $^{-1}$  (Winter),  $0.7\text{ }^{\circ}\text{C}$  decade $^{-1}$  (Spring),  $0.4\text{ }^{\circ}\text{C}$  decade $^{-1}$  (Summer), and  $0.8\text{ }^{\circ}\text{C}$  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



**Fig. 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

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).

## 5 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 to 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). Significant increases in decadal vessel counts in the shoulder seasons for all vessel types combined annually (Table 2), increasing SAT trends to a maximum of 1.8 °C decade<sup>-1</sup> in the winter months (not shown), and declining sea ice in all months of the year (e.g. Fig. 4, Table 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 (Fig. 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 (Fig. 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. 2013).

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 ship 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.

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## Author contributions

L.P., S.H., and C.D. designed methods. L.P. performed data analysis. L.P., S.H., C.D., J.D., and L.C. wrote the paper.