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Key Points:
- First observational coupled spatial analysis of the influence of declining sea ice on increasing ship activity in the Canadian Arctic
- Shipping activity increases are significantly correlated to declining sea ice in several regions
- The presence of multiyear ice seems to influence shipping activity more than seasonal first-year ice

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The influence of declining sea ice on shipping activity in the Canadian Arctic

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Abstract Significant attention has focused on the potential for increased shipping activity driven by recently observed declines in Arctic sea ice cover. In this study, we describe the first coupled spatial analysis between shipping activity and sea ice using observations in the Canadian Arctic over the 1990–2015 period. Shipping activity is measured by using known ship locations enhanced with a least cost path algorithm to generate ship tracks and quantified by computing total distance traveled in kilometers. Statistically significant increases in shipping activity are observed in the Hudson Strait (150–500 km traveled yr^{-1}), the Beaufort Sea (40–450 km traveled yr^{-1}), Baffin Bay (50–350 km traveled yr^{-1}), and regions in the southern route of the Northwest Passage (50–250 km traveled yr^{-1}). Increases in shipping activity are significantly correlated with reductions in sea ice concentration (Kendall's tau up to −0.6) in regions of the Beaufort Sea, Western Parry Channel, Western Baffin Bay, and Foxe Basin. Changes in multiyear ice-dominant regions in the Canadian Arctic were found to be more influential on changes to shipping activity compared to seasonal sea ice regions.

1. Introduction

Declining sea ice within Canadian Arctic waters is of particular interest to the global shipping community due to the potential of the Northwest Passage through the Canadian Arctic Archipelago (CAA) becoming a seasonally viable alternative shipping route (Figure 1). Recent studies using state-of-the-art climate models have suggested that navigation through the Canadian Arctic will likely be easier and faster by the mid-21st century [e.g., *Stephenson et al.*, 2011; *Smith and Stephenson*, 2013; *Melia et al.*, 2016; *Barnhart et al.*, 2015]. Statistically significant and divergent trends in summer sea ice area (-2.1681×10^4 km yr^{-1}) and shipping activity (2.2 ships yr^{-1}) are found within the Canadian Arctic domain from 1990 to 2015 (Figure 1). However, the detrended correlation between the two variables is low [*Pizzolato et al.*, 2014]. Despite speculation that declining sea ice may be, to some extent, influencing shipping trends in the region, several other studies have suggested that tourism trends, commodity prices, and natural resource development are likely much more influential than declining sea ice [e.g., *Bensassi et al.*, 2016; *Brigham*, 2011; *Dawson et al.*, 2014; *Eguíluz et al.*, 2016]. Even with these varying perspectives, the spatial variability of sea ice and its corresponding influence on shipping in Canadian Arctic waters has not been quantified over multidecadal time periods. The spatial variability of sea ice decline is an important consideration, especially in the Canadian Arctic, where declines vary between 2.9 and 11.3% decade^{-1} depending on the region [*Tivy et al.*, 2011; *Derksen et al.*, 2012]. Here we contribute to the discussion about shipping and sea ice by spatially quantifying the observed changes in shipping activity (kilometers traveled) together with sea ice (concentration) during the shipping season (June–October) in the Canadian Arctic over a 26 year period from 1990 to 2015.

2. Data and Methods

The primary data sets used in this analysis covering the domain illustrated in Figure 1 were ship data from Vessel Traffic Reporting Arctic Canada Traffic Zone (NORDREG zone [*Pizzolato et al.*, 2014]), sea ice concentration data from the Canadian Ice Service Digital Archive (CISDA [*Canadian Ice Service*, 2011, 2007; *Tivy et al.*, 2011]), and 2-Minute Gridded Global Relief Data (ETOPO2v2 [*National Centers for Environmental Information*, 2006]). Daily ship positional data in the NORDREG zone from 1990 to 2015 was converted into a distance traveled metric by using a least cost path (LCP) approach. Ships within this archive represent a wide variety of ship types including pleasure crafts, bulk carriers, government vessels and icebreakers, fishing vessels, and

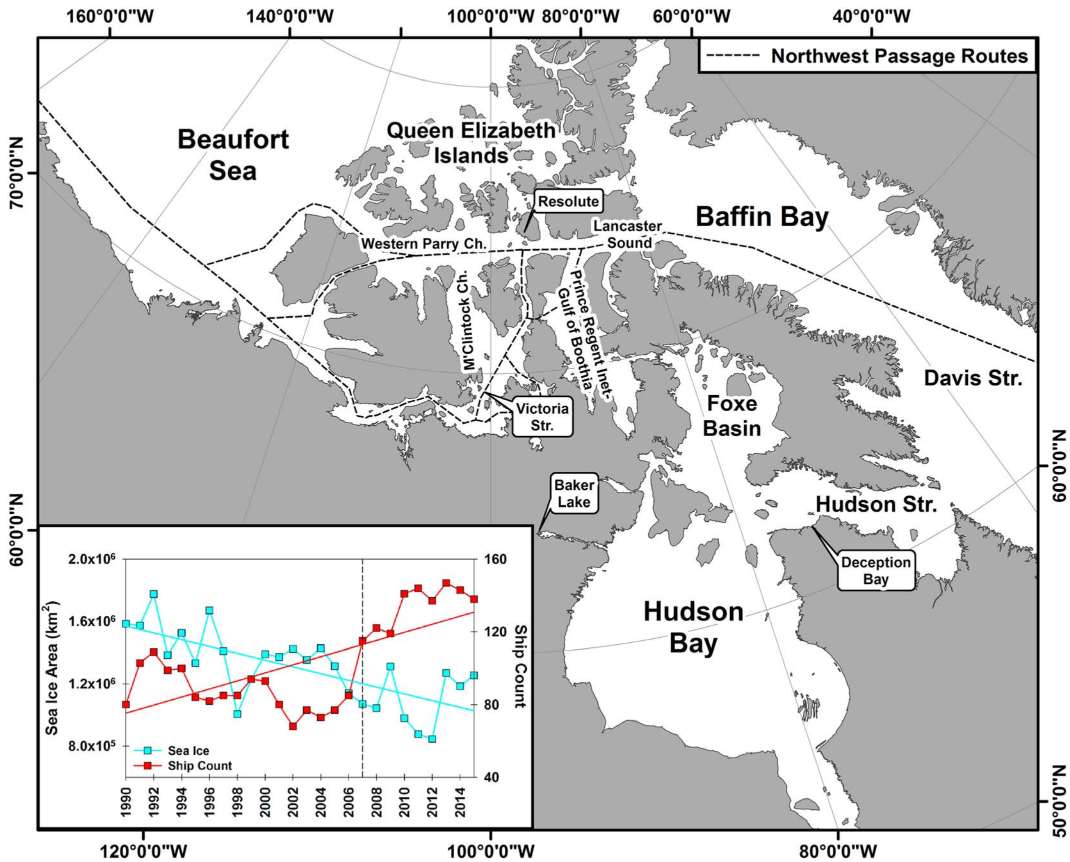

Figure 1. Map of the Canadian Arctic sea ice domain used in this study. The inset illustrates the time series of total sea ice area (km^2) and unique ship count by vessel name Canadian Arctic sea ice domain from 1990 to 2015. The vertical dashed line indicates the 2007 significant step change in shipping activity identified by *Pizzolato et al.* [2014]. Ship count data are from the Vessel Traffic Reporting Arctic Canada Traffic Zone (NORDREG zone), and sea ice area data are from the Canadian Ice Service Digital Archive (CISDA) [*Canadian Ice Service*, 2011, 2007].

passenger, cargo, and tanker ships [see *Pizzolato et al.*, 2014]. In order to connect known ship locations (points), a weighted cost surface was generated to reconstruct a ships route based on the relative impedance of each criterion to a ships safe routing where 100 is a severe impedance and 0 is little impedance using three cost parameters. For total sea ice concentration, a concentration of 10 tenths was assigned a cost of 100 declining to 0 tenths, which was assigned a cost of 0. The ice chart selected for the cost surface was the closest in date to the start point of the pair of ship points. Bathymetry was assigned a cost of 100 when it exceeded 0 m as this was considered land, and a cost of 0 when it exceeded the reported draft from the NORDREG ship archive plus 3 m of safe under keel clearance (i.e., maximum draft). Costs of 25 and 50 were assigned for depths between 0 m and the reported draft, and the reported draft to maximum draft, respectively. In the absence of ship draft data, 8 m was prescribed for the minimum draft based on the mean value of available ship draft data ($n = 596$) over 1990 to 2013. Finally, the distance from land was reclassified with the cost increasing linearly from 0 at 25 km or more from the coastline, to 100 at the coastline. Distance from land and bathymetry were employed as metrics in the LCP analysis in addition to sea ice because of the frequency of ships present near the coastline where the bathymetry (due to mixed pixels of land and water) prevented ships from going near communities where we know ships went based on the input point data. Within the study area, if there was coverage by an ice chart, the final weighted cost surface using the reclassified cost surfaces consists of 50% total sea ice concentration, 25% bathymetry, and 25% distance from land. For areas without sea ice information (i.e., no ice chart for the region), the weighted cost surface consisted of 75% bathymetry and 25% distance from land.

The LCP approach generated 68,995 voyage segments representing 4303 unique ship voyages (defined by entrance/exit of the Canadian Arctic domain) over the 1990 to 2015 time series. We then used the

Automated Identification System (AIS) ship data by exactEarth® to assess the ability for the LCP approach to accurately reconstruct ship voyage segments from the known ship points by using the weighted cost surfaces. AIS data were acquired for 2010 and improve upon the frequency of ship reporting with reporting every millisecond, second, or hour, coincident with satellite passes. Using a random sample of 25 LCP-derived ship voyage routes spanning 137×10^3 km from 2010 that were in both the AIS and LCP data sets, we were able to conduct error and sensitivity analysis. This allowed us to establish the ability to use the LCP approach to generate shipping activity grids used in the subsequent spatiotemporal trend and correlation analyses. The displacement from each independent AIS data point was calculated to the nearest generated LCP voyage segment for the same date generating a median error of 5.6 km. Intermodel sensitivity (the model's ability to predict the correct route even when median points are removed) was examined by recalculating the LCP between every other known ship point (e.g., points 1 and 3) and every two known points (e.g., 1 and 4) in the subset. The median displacement for ship tracks generated with median points removed to the nearest recalculated LCP of the same date is 8.21 km (one point removed), and 8.47 km (two points removed). Overall, this suggests that as long as the chosen grid cell size for analysis is greater than 8.5 km, we can be confident that the true voyage falls within the grid cell estimated by the LCP approach.

The coefficient of variance (CV) was used to establish an appropriate cell size for statistical analysis. The CV was calculated for each cell in the shipping season time series on three different grid scales (25 km, 50 km, and 100 km). At 100 km, 72% of the cells for the given variable had a CV of 2 or less; thus, 100 km was deemed appropriate for subsequent analysis. Finer grid cells were excluded as they did not meet our threshold of at least 70% of the grid cells having a CV of 2 or less. Sea ice concentration was subsequently sampled to a 100 km grid to coincide with the shipping data. At that resolution, 100 km traveled within a cell is approximately equal to 1 ship transit equivalent, that is one ship passing through the grid cell.

Trend analysis was performed on the gridded shipping activity and sea ice concentration data using the Zhang method of Sen's slope [*Zhang et al.*, 2000]. To analyze the correlation between the two variables, we use a correlation analysis method that carefully accounts for years when a grid cell does not have any shipping activity. This correlation analysis method was performed on each grid cell by using the following procedure:

1. If there is no shipping activity for more than 1 year, we find the highest ice concentration among the years with shipping activity.
2. We then identify all years with (1) no shipping activity and (2) ice concentration higher than the maximum found in (1). Of these identified years, we then retain the year with lowest sea ice concentration and discard the remaining years.
3. Any year without shipping activity and where ice concentrations are below the maximum found in (1) are retained.
4. Steps (1)–(3) adjust for ties in shipping activity, which allows us to compute Kendall's tau-a rank correlation (which does not make adjustments for ties) by using a 95% confidence level determined by using a two-tailed t test.
5. The correlations between the raw and the detrended data were computed. The lowest correlation of the two was then selected. This selection ensures that in the event of data with a shared trend, the correlations were independent of shared trends between the data sets.

3. Spatial Distribution of Shipping Activity and Sea Ice Concentration

We first investigate the 26 year spatial distribution of mean shipping activity and sea ice concentration and then compare it to 2007–2015 anomalies. We use the latter period because of a significant ~20% increase in ships count in the Canadian Arctic that occurred in 2007 [*Pizzolato et al.*, 2014] (Figure 1). Mean shipping activity (kilometers traveled) in the Canadian Arctic from 1990 to 2015 occurred primarily in regions of north Hudson Bay, the Hudson Strait, Davis Strait, Baffin Bay, Lancaster Sound, and the south Beaufort Sea (Figure 2a). The spatial distribution is similar to the pattern illustrated by *Eguíluz et al.* [2016] based on AIS data from 2010 to 2014. Regions of high shipping activity typically correspond to areas of lighter sea ice concentration, as the majority of high sea ice concentration is located in central CAA and the north regions of Beaufort Sea (Figure 2c).

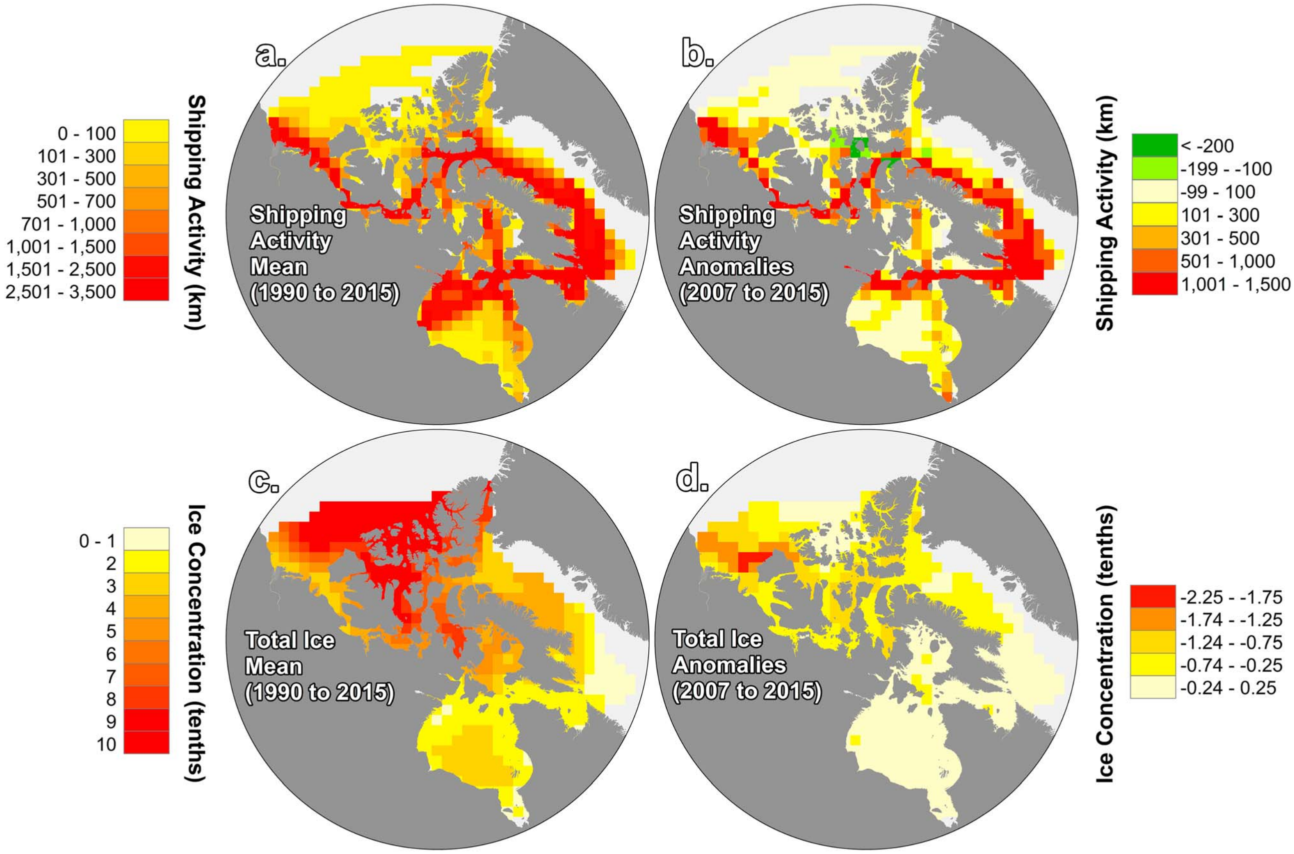

Figure 2. Spatial distribution of June to October shipping activity (km) for (a) 1990 to 2015 mean, (b) 2007 to 2015 anomalies from 1990 to 2015 mean, total sea ice concentration (tenths) for (c) 1990 to 2015 mean, and (d) 2007 to 2015 anomalies from 1990 to 2015 mean.

Since 2007, strong positive anomalies in shipping activity up to 15×10^2 km or ~15 more transit equivalents traveled are found the Hudson Strait, Davis Strait, the Beaufort Sea, and regions along the southern route of the Northwest Passage through the CAA (Figure 2b). Negative anomalies in shipping activity are present, but they are small and primarily located in the area surrounding Resolute (Figure 2b). Coincident with increases in shipping activity, lighter total sea ice conditions with anomalies up to −2.25 tenths are apparent throughout many regions of the Canadian Arctic, particularly in the Beaufort Sea from 2007 to 2015 (Figure 2d).

4. Spatial Trends and Correlations Between Shipping Activity and Sea Ice Concentration

The spatial distribution of shipping activity trends in the Canadian Arctic over the 1990–2015 period indicates that the Hudson Strait is experiencing the strongest statistically significant (95% confidence level) increase in shipping activity of ~451–550 km yr^{-1} or ~4.5–5.5 transit equivalents yr^{-1} (Figure 3a). This is followed by the Beaufort Sea (50–450 km yr^{-1} or ~0.5–5.5 transit equivalents yr^{-1}), several regions in southern route of the Northwest Passage through in the CAA (up to 250 km yr^{-1} or ~2.5 transit equivalents yr^{-1}) and in regions in the Davis Strait and southern Baffin Bay (up to ~350 km yr^{-1} or ~3.5 transit equivalents yr^{-1}) (Figure 3a). The only region experiencing a statistically significant (95% confidence level) decline in shipping activity across the entire Canadian Arctic domain is the area surrounding Resolute at ~50–150 km traveled yr^{-1} (~0.5–1.5 transit equivalents yr^{-1}), which is likely due to the closure of the Polaris Mine in 2002 (Figure 3a).

Negative trends in total sea ice concentration over the 1990–2015 period are present within the Canadian Arctic, with the strongest significant negative trends found in the Beaufort Sea (0.05 to 0.24 tenths yr^{-1}) (Figure 3b). Victoria Strait, Lancaster Sound, and Baffin Bay are also experiencing total ice concentration

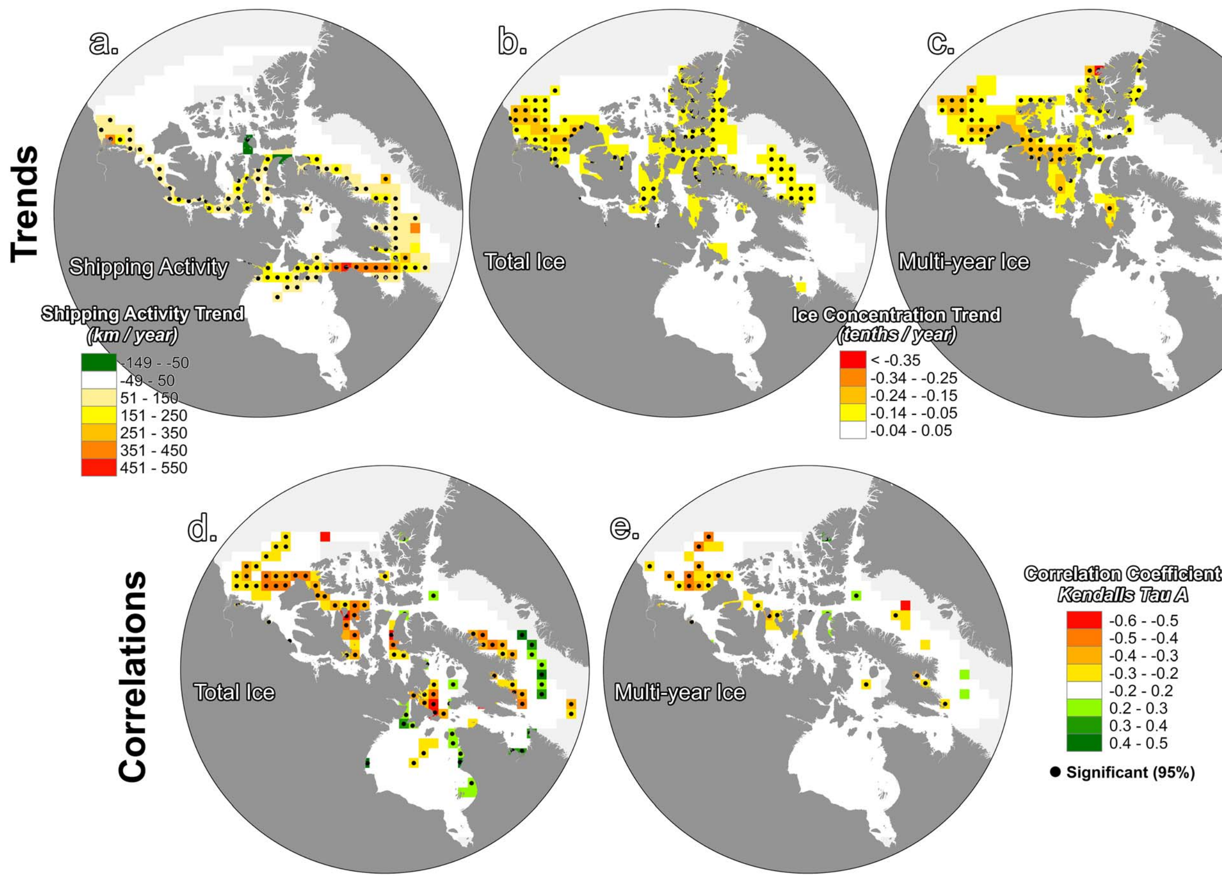

Figure 3. Theil-sen slope of the trend from 1990 to 2015 for (a) shipping season shipping activity (km yr^{-1}), (b) shipping season total ice concentration (tenths yr^{-1}), and (c) shipping season multiyear ice concentration (tenths yr^{-1}). Significant trends (95% confidence level) are only reported outside of a −49 to 50 km yr^{-1} threshold for shipping activity and below the −0.05 threshold for total and multiyear sea ice. Kendall's tau-a correlation coefficient between (d) shipping activity and total sea ice concentration and (e) shipping activity and multiyear sea ice concentration. Only significant correlations (95% confidence level) greater than 0.2 or less than −0.2 are reported.

declines between 0.14 and 0.05 tenths yr^{-1} (Figure 3b). For multiyear ice, significant negative trends of up to 0.34 tenths yr^{-1} are primarily found in the Beaufort Sea and Western Parry Channel (Figure 3c). The absence of significant sea ice trends in the Hudson Bay complex is likely linked to the typically low sea ice conditions during the months of June to October [*Canadian Ice Service*, 2011], and that our analysis period begins in 1990, while most of the sea ice decline in Hudson Bay had already occurred prior to this period [*Hochheim and Barber*, 2014].

Given the observed declines in sea ice concentration and increases in shipping activity, the question remains of whether the two are correlated in the Canadian Arctic. Figure 3d illustrates that significant negative correlations between shipping activity and total sea ice concentration up to −0.6 are found in the Beaufort Sea, Western Parry Channel, M'Clintock Channel, Victoria Strait, Prince Regent Inlet-Gulf of Boothia, Baffin Bay, and Foxe Basin representing 14% of the entire Canadian Arctic domain. However, both significant divergent trends and correlations are present only in the south Beaufort Sea, Victoria Strait, and south Baffin Bay. Previous studies have suggested that decreasing sea ice is not the only factor influencing increasing shipping, and in fact, may not be the primary driver, but instead an enabler of increased activity [e.g., *Bensassi et al.*, 2016; *Brigham*, 2011; *Dawson et al.*, 2014; *Eguíluz et al.*, 2016]. While this may be true in many regions, our analyses shown in Figure 3d suggest that sea ice variability has some direct influence on shipping activity in some regions of the Canadian Arctic. It should be noted that the significant correlations that range from −0.2 to −0.6 are relatively low in some regions.

There are also regions within the Canadian Arctic domain where sea ice conditions exert minimal, if any influence on shipping activity. In Lancaster Sound, shipping activity remained relatively constant at ~29×10^3 km

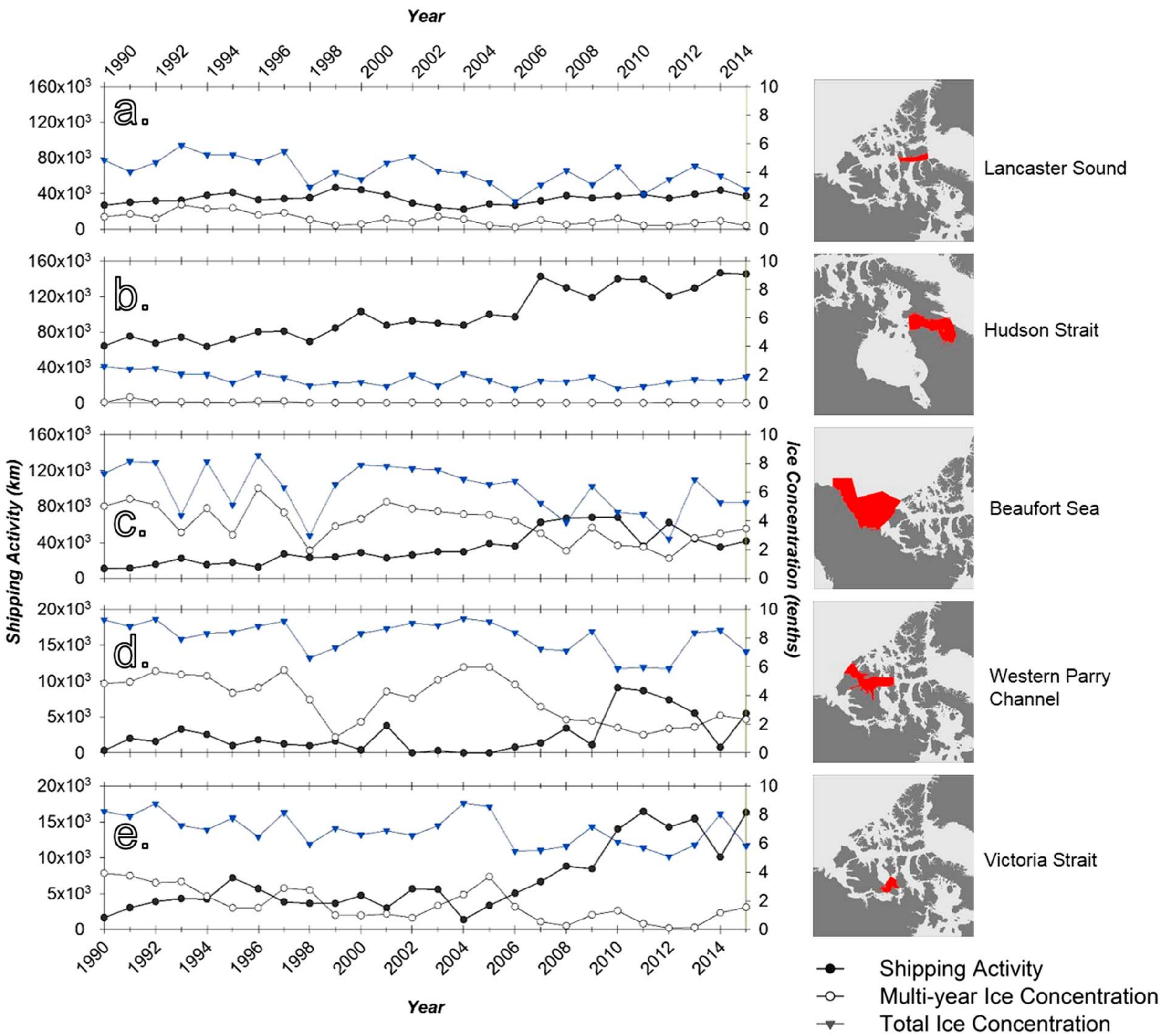

Figure 4. Time series of shipping activity (km), total sea ice concentration, and multiyear sea ice concentration from 1990 to 2015 for (a) Lancaster Sound, (b) Hudson Strait, (c) Beaufort Sea, (d) Western Parry Channel, and (e) Victoria Strait.

traveled (~290 transit equivalents) annually that was independent of large fluctuations in total sea ice concentration from 2 to 6 tenths (Figure 4a). Hudson Strait experienced no significant declining sea ice trend (Figure 3b), yet the region has had the strongest increases in shipping activity (Figure 3a). As shown in the Hudson Strait time series, shipping activity has steadily increased over the 1990–2015 period (up to ~550 km yr^{-1} or ~5.5 transit equivalents yr^{-1}), although the ice concentration remained largely unchanged (Figure 4b). We suggest that this is largely related to mining operations out of Deception Bay and Baker Lake. Finally, many regions along the southern route of the Northwest Passage also experienced increases in shipping activity (Figure 3a) but were found to have no correlation to multiyear or total sea ice concentration (Figure 3d).

5. Shipping Activity in Seasonal Versus Multiyear Ice Regions

Perhaps the most compelling spatial relationship revealed in our analysis of the Canadian Arctic is between shipping activity and multiyear sea ice. Even in low concentrations, multiyear ice is the most significant impediment to transiting ships because of its high mechanical strength [*Timco and Weeks*, 2010]. Canadian Arctic regions that contain multiyear ice appear to influence shipping activity more so than seasonal ice regions. The northern Beaufort Sea, Queen Elizabeth Islands, Western Parry Channel, M'Clintock Channel, and

Victoria Strait regions are known to contain appreciable of amounts multiyear ice [e.g., *Canadian Ice Service*, 2011]. This known hazard is reflected in the shipping records both in terms of minimal shipping activity when looking at the spatial distribution and trends in these regions (Figures 2a and 3a). Additionally, low amounts of shipping activity can also be attributed to few communities in these areas (thus requiring less re-supply) and few economic or transit-related reasons for being in some parts of the Canadian Arctic Archipelago such as the Queen Elizabeth Islands. Conversely, seasonal ice regions of Baffin Bay and the Hudson Bay complex correspond to where the majority of shipping activity takes place and where positive trends in shipping activity trends are most significant (Figures 2b and 3a).

Within the CAA, increased shipping activity in the Western Parry Channel, M'Clintock Channel, and Victoria Strait appears to only occur when multiyear ice concentration is very low (e.g., Figures 4d and 4e). These regions contain an intricate mix of seasonal first-year ice and multiyear ice that is very spatially dynamic during the summer melt season [e.g., *Howell et al.*, 2009, 2013a] compared to a more consistent multiyear ice regime in locations such as the Beaufort Sea. It is likely that this dynamic intricate mix is responsible for the more significant correlations with total sea ice compared to multiyear ice (which only represents 4% of the entire Canadian Arctic domain) (Figures 3d and 3e) given the 100 km cell size. However, evidence for the influence of multiyear ice can be seen by considering the individual time series for these regions. In the Western Parry Channel, minimal shipping activity and high total ice concentrations (~8–9 tenths) occur for all years except between 2010 and 2012 when shipping activity increased from 43.72×10^2 to 79.00×10^2 km traveled (~43.7–79.0 transit equivalents), and multiyear ice decreased almost below 2 tenths (Figure 4d). Indeed, multiyear ice concentrations have remained relatively low since 2008, but total ice concentrations in the Western Parry Channel region are still high because the region is known to generate multiyear ice from first-year seasonal ice surviving the melt season, and being promoted to multiyear ice, in addition to multiyear ice advection from higher-latitude regions [*Howell et al.*, 2009]. The 2010–2012 period exhibited the lowest ice years in the CAA since 1968, with virtually ice-free conditions in the Western Parry Channel [*Howell et al.*, 2013b]. In the Victoria Strait region, shipping activity nearly tripled from 2006 to 2013 (up to 15 000 km traveled or ~150 transit equivalents), while multiyear ice in the region remained relatively low at under 2 tenths concentration (Figure 4e). Thick multiyear ice is known to gradually migrate to Victoria Strait from higher-latitude regions of the CAA [*Howell et al.*, 2009; *Haas and Howell*, 2015], but Figure 4e indicates that multiyear ice is certainly less from 2006 to 2015 compared to the period from 1990 to 2005. Moreover, the Victoria Strait region has been virtually ice-free at some point during the June-October shipping seasons for every year from 2006 to 2015 with the exception of 2014.

For the Beaufort Sea, the position of the multiyear ice edge in the Arctic Ocean is the primary physical factor influencing shipping for the region. Numerous studies have demonstrated that the Beaufort Sea has recently (starting in ~2007) shifted to a younger and thinner ice cover which has difficulty surviving the melt season [e.g., *Maslanik et al.*, 2011; *Krishfield et al.*, 2014; *Howell et al.*, 2016], thus facilitating increased areas of open water in the region. Significant correlations are primarily found in the Beaufort Sea (Figure 3e), and the time series of shipping activity and multiyear ice concentration further illustrates gradual increases and decreases from 1990 to 2015, respectively (Figure 4c).

6. Conclusions

Based on known ship points, we have constructed ship tracks from 1990 to 2015 by using a least cost path approach that takes into account bathymetry and observed total sea ice concentration. These ship tracks allowed us to compute the distance traveled by vessels across the Canadian Arctic domain and on uniform grids at different resolutions. The distance traveled by vessels has been used in this study as a way to measure shipping activity. This measure was used because it has the desired property of being a scale-independent accounting of ship activity. With this measure, we quantified the spatial relationships between shipping activity and sea concentration within the Canadian Arctic over a 26 year time period from 1990 to 2015. Shipping activity has significantly increased in Hudson Strait, Beaufort Sea, regions in southern route of the Northwest Passage, Davis Strait, and southern Baffin Bay. Significant negative correlations between shipping activity and total sea ice concentration were found in the Beaufort Sea, Western Parry Channel, M'Clintock Channel, Victoria Strait, Prince Regent Inlet-Gulf of Boothia, Baffin Bay, and Foxe Basin, representing 14% of the entire Canadian Arctic domain. Both significant divergent trends and correlations are present between total sea ice concentration and shipping activity only in the south Beaufort Sea, Victoria Strait, and south Baffin Bay. Shipping activity increased independent of sea ice conditions in Hudson Strait, Lancaster Sound, and several regions of the southern route of the Northwest Passage.

Multiyear ice is the most significant hazard to transiting ships, and this relationship appears to be robust when considering the spatial distribution and trends in shipping activity in Canadian Arctic from 1990 to 2015. Despite negative trends in multiyear ice concentration, it seems that the shipping industry in Canadian Arctic waters is still mindful of multiyear ice regions particularly along the northern route of the Northwest Passage (i.e., the Western Parry Channel). Several modeling studies have suggested that the northern route of the Northwest Passage will be able to support increases in shipping activity in the future [e.g., *Stephenson et al.*, 2011; *Smith and Stephenson*, 2013; *Melia et al.*, 2016]. However, the observational evidence presented in this study indicates that very little shipping activity has actually occurred within the northern route of the Northwest Passage despite the persistence of low ice conditions since 2007. Moreover, numerous process studies that indicate thick multiyear ice from the Arctic Ocean will continue to flow into the northern route as long as multiyear ice remains present on the north facing coast of the CAA [e.g., *Howell et al.*, 2009; *Howell et al.*, 2013a; *Haas and Howell*, 2015], and climate models indicating the last remaining summer sea ice in the Arctic will remain on the north facing coast of the CAA [*Wang and Overland*, 2012; *Laliberté et al.*, 2016]. Therefore, it seems unlikely the northern route of the Northwest Passage will be a viable shipping route for several decades to come.

By identifying the spatial variability of shipping within the Canadian Arctic from 1990 to 2015, this study now provides a basis for better understanding the interactions and implications that a changing physical environment may have on regional shipping activity. Knowing the empirical relationship between sea ice concentration and shipping activity allows for more robust understandings of the sea ice-shipping relationship and provides a benchmark for establishing future shipping scenarios that ideally include both physical and socioeconomic conditions. However, there remains a need to more fully examine the decision-making processes of ship operators in the region including focused study of the precise influence that changing ice regimes have on "go-no-go," and other navigation decisions. The study results have strong utility for current decision-making in the region, and the results are useful in assisting with operational route planning, aiding federal and regional decision makers regarding asset management and deployment (i.e., ice-breaker positioning and timing, patrol vessels, and other search and rescue assets), marine infrastructure and investment (i.e., ideal locations for places of refuge and general infrastructure), and policy and regulatory needs.

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