

# **Northwest Passage Shipping in the 21<sup>st</sup> Century**

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## **Capstone Statement**

In recent decades, the Arctic has been warming at double the rate of the global average. This has led to a significant loss of ice cover, including 33% of sea ice extent and 63% of total ice volume in September (Fetterer et al., 2017; Schweiger et al., 2011). There is renewed interest in trans-Arctic shipping as the diminishing ice cover significantly reduces costs and journey times between Asia, Europe, and North America. We will examine the suitability of various routes through the Northwest Passage and determine the optimal route based on ice conditions, bathymetry, ship attributes, and various other factors throughout the 21<sup>st</sup> century.

## Background

The Arctic is an infamously hazardous and intriguing marine environment. Explorer Roald Amundsen completed the first transit of the Northwest Passage (NWP) in 1906; a three year transit at the time (Ellis and Brigham, 2009, 37-39). It is a harsh setting for marine activity; the sun sets for six months, temperatures plunge, it is remarkably uncharted, and, most importantly, it is defined by ice. Yet, in 2018, a commercial vessel made a winter trans-Arctic voyage unescorted by an icebreaker for the first time in history (Darby, 2018).

	Distance (km)	% reduction from Suez Canal	% reduction from Panama Canal
Panama Canal	24,000	n/a	n/a
Suez Canal	21,000	n/a	n/a
NWP	13,600	35%	43%

*Table 1: Approximate distances of trans-oceanic sea routes and the reductions offered by the Northwest Passage.*

The Arctic today is climatically dynamic and particularly sensitive to anthropogenic climate change. “Arctic amplification,” the term for the increased warming above the Arctic Circle, has driven warming at more than twice the rate of the global average (Overland et. al., 2017). One simple mechanism explaining this amplification has been the ice-albedo feedback, wherein highly reflective ice melts and becomes replaced by the darker, less-reflective ocean surface, which, in turn, fosters more absorption of radiation and more consequent melting (Pithan and Mauritsen, 2014, 181-182).

The NWP can be significantly shorter than traditional routes, as displayed by Table 1. It encompasses a bundle of marine routes between the Atlantic and Pacific Oceans that weaves through the Canadian Arctic Archipelago. There are five recognized routes with notable variations in their different legs (Liu et. al., 2017, 92). Commercial shipping has increased in these routes due to the melting of Arctic sea ice; both the amount of ice and the duration of ice cover have affected route patterns and economic usage. The Northwest Passage is likely to be the choice of more and more merchant ships, if global warming continues at its current rate (Liu et. al., 2017, 91). During the late 20<sup>th</sup> and early 21<sup>st</sup> century, Arctic sea ice has been observed to be decreasing in both thickness and extent. It is possible that no sea ice would survive during the summer season in the near future. Arctic sea ice loss has opened up new marine corridors as well as extending the length of the shipping season (Ellis and Brigham, 2009, 4). The month of September typically represents the annual minimum of sea ice extent and thickness, and it is understandably the peak of the navigation season. By some predictions, the Arctic will reach ice-free September conditions by 2040 (Holland et. al., 2006, 1).

The implications of these changes are potentially global, particularly in an economic realm (Melia, 2016). Observations that show high year-to-year variability of sea ice coverage create further uncertainty regarding whether ships are able to make safe passage (Ellis and Brigham, 2009, 112). Potential reduction in travel distances provides a large financial incentive for the commercial shipping industry to explore Arctic sea routes.

## Conceptualization

The suitability of a shipping route through the Northwest Passage depends on the climatology of the area's ice, the ability of the vessel, and the bathymetry along the route. We aim to identify routes with acceptable ice and bathymetric conditions for a vessel of a specific polar class. Our original data layer will involve digitized shipping routes as detailed in Liu et al (2017) and Ellis and Brigham (2009), and referenced for accuracy to MarineTraffic data. These routes will be analyzed for their suitability and scored based on which is optimal for traveling through the Northwest Passage during climatological periods.

Figure 1 displays this study's conceptualization diagram. Our key concepts, as detailed above in the data section, are ice conditions, ship ability, and geophysical landscape. These three variables largely determine the ability of a ship to feasibly pass through a given route. We are specifically looking at ships of Polar Class 6, and the resulting operationalized variables depict the favorable environmental and hydrological conditions for this class.

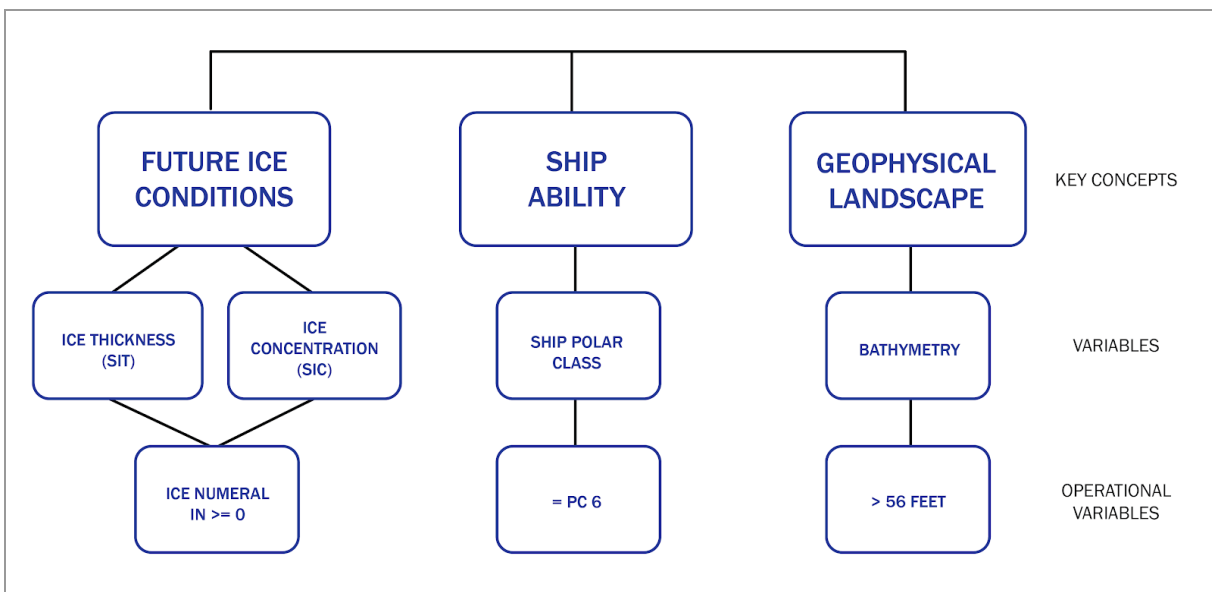


Figure 1: Conceptualization diagram

## Data and Methods

### *The CESM*

The Community Earth System Model, version 1 (CESM1) is a fully coupled global circulation model (GCM) created by the National Center for Atmospheric Research (NCAR) that effectively captures Arctic sea ice conditions (Hurrell et al., 2013). This paper will utilize the Large Ensemble (LENS) output from the CESM. LENS is a unique dataset for 21st century global climate models, consisting of 40 ensembles initiated with round-off differences in air temperature ( $\sim 10^{-14}$  K) (Kay et al., 2015). From 1920–2005, the ensembles received historical climate forcings and are subject to representative concentration pathway (RCP) 8.5 (8.5 W/m<sup>2</sup> of forcing from greenhouse gases) from 2006–2100. Because the resulting ensemble spread results from identical forcings, ensemble variability is generated solely due to internal climatic variability. The internal variability is extremely useful for identifying periods of large climate sensitivity (Kay et al., 2015). Figure 2 shows the skill of the CESM at capturing pan-Arctic sea ice extent, compared to observations from the Sea Ice Index (Fetterer et al., 2017). Because of the long periods needed for the computation of GCMs, there is limited data available on other scenarios besides RCP8.5. In fact, NCAR does not currently provide any available, open-source CESM experiments besides the LENS in its current state. Finally, RCP8.5, the “high-emissions” scenario, has been shown to overestimate Arctic sea ice (Figure 2).

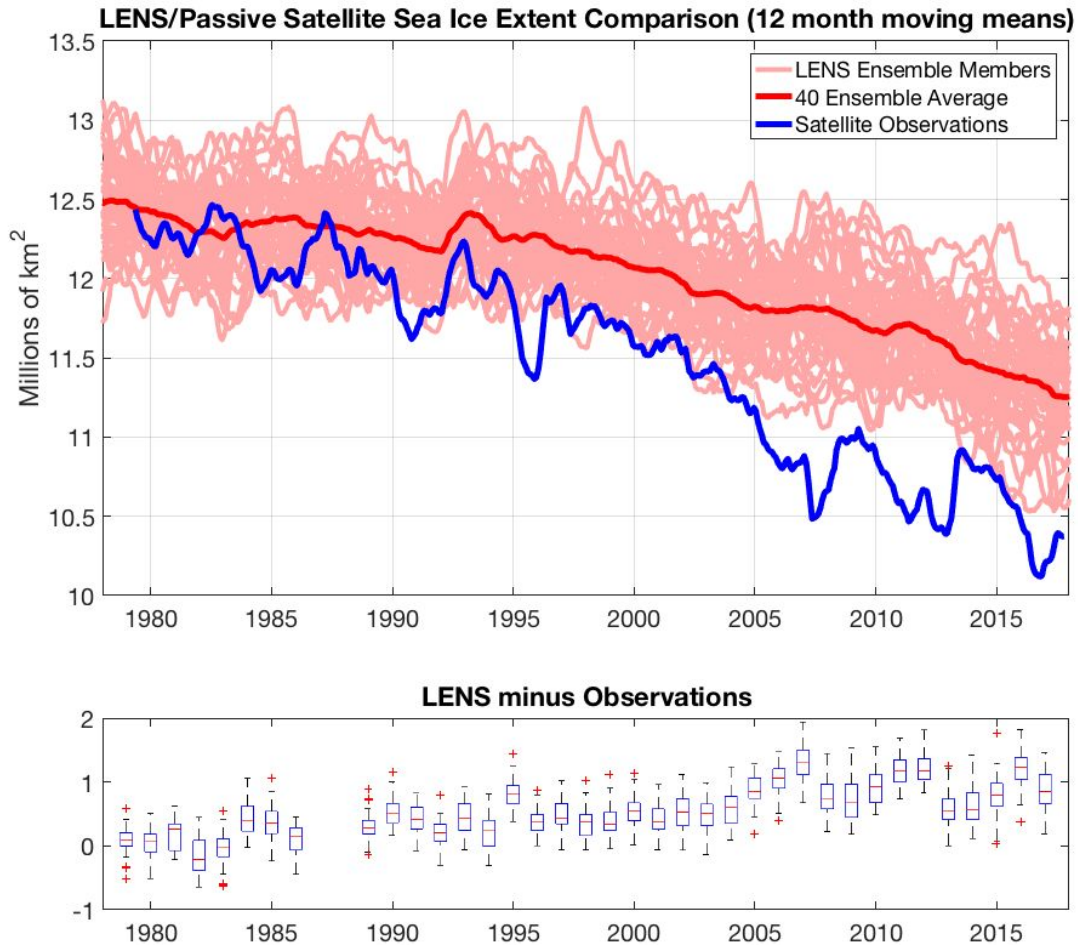


Figure 2: Top: Comparison of 40 LENS ensemble members, and ensemble average, to satellite sea ice extent observations. Bottom: Bias of LENS sea ice extent averaged for each year. Gaps in plot represent missing observations.

Ice data from the LENS dataset is approximately 1° horizontal resolution featuring a displaced North Pole grid. Several output variables for sea ice are available, however this study will utilize sea ice concentration (SIC) and sea ice thickness (SIT).

### *Ice Numeral*

This study will utilize a marine shipping metric, the Ice Numeral (IN), which was first prescribed by Transport Canada as part of the Arctic Ice Regime Shipping System (AIRSS)

(Timco et. al., 2005). The purpose of the IN is to give mariners a simple metric for determining if ice conditions are safe for passage. The IN is imposed on mariners transiting the Canadian Arctic by regulation. The equation for Ice Numeral is:

$$IN = \sum_{i=1}^n C_i \times IM_i$$

where  $C_i$  and  $IM_i$  are the concentration and Ice Multiplier of ice type  $i$ , respectively, for  $n$  ice types. Here, concentration ranges from 0 to 10, such that open water is a zero and 100% ice cover is a 10. Ice Multiplier is an integer that is a function of a vessel's ice capability and the age and thickness of the ice. The summation accounts for the fact that multiple types of ice can occur together, in addition to open water that exists when total SIC is less than 100%. Ice multiplier ranges from -4 (thickest ice, or greater than ~1.5 meters for a vessel with no ice strengthening) to 2 (open water). This yields a range of IN from -40 (100% coverage of thickest ice) to 20 (100% coverage of open water). IM values are prescribed by AIRSS, and were altered for use in modelling by Smith and Stephenson (2013), these values have been listed in Table 2. In the Canadian Arctic, a vessel is not permitted to transit a negative IN regime, but may proceed through positive or neutral regimes (Transport Canada, 2010).

<b>Ice Multiplier</b>	<b>Thickness Range (cm)</b>
2	$T < 70$
1	$70 \leq T < 120$
-1	$120 \leq T < 151$
-3	$151 \leq T < 189$
-4	$189 \leq T$

*Table 2: List of Ice Multiplier (IM) values for a Polar Class 6 (PC6) vessel, as prescribed by Smith and Stephenson (2013).*

A team from the National Research Council of Canada investigated a sample of ship transits for their INs and whether or not ice damage was sustained (Timco & Kubat, 2001). They determined that the system performed “reasonably well,” although damage was also shown to be correlated to vessel speed, which is not included in the IN calculation. IN was calculated for each applicable grid cell from the LENS, utilizing the corresponding SIT and SIC.

For simplicity, this study will analyze LENS ensemble averages, rather than investigate individual ensemble members. This procedure gives a literal sense of the average of the model output, but at the sacrifice of the extremes and temporal variability that the individual ensembles experience. However, in an analysis of climatic projections, this is reasonable, since the mean state of the system is the desired effect. The LENS output was further broken into five year averages. Five years is much smaller than a typical climatological period, but is feasible for our purposes, as the state of the Arctic climate has changed rapidly in recent years. In our project, the operationalized variable for ice climatology then becomes  $IN \geq 0$  for a five year climatic average.

## *Ship Ability*

The International Association of Classification Societies (IACS) designates a system for classifying ships that can operate in Arctic waters, known as the “Polar Class” (IACS, 2016, I1-2). Although not the only system in use, Polar Class has been conventionally used by other studies on Arctic shipping (Smith and Stephenson, 2013). Here, we will focus on vessels classified as Polar Class 6 (PC6), which are rated for summer and autumn operations in medium, first-year ice. Using the methods of Smith and Stephenson (2013, 3-4), we have adapted the AIRSS IM designation to be a function of SIT and a PC6 vessel (Table 2).

## *Geophysical Landscape*

The bathymetry of the ocean floor throughout the region plays an important role in which areas are navigable by PC6 vessels. Canada’s Arctic coastline consists of over 4.4 million square kilometers of land and over 36,000 islands (Fisheries and Oceans Canada, 2017). For potential navigators, the accuracy of the surveys provided by the Canadian Government is essential to navigating a route through the Northwest Passage. Currently, about 10% of the Arctic waters have been surveyed with only 1% meeting modern standards (Fisheries and Oceans Canada, 2017). We have decided to use the International Bathymetric Chart of the Arctic Ocean Version 3.0 (IBCAO 3.0) for input data that is best represented.

Although included within the CESM, river bathymetry is crucial in understanding sea ice patterns in the Arctic. Ngheim et. al. (2014) presented a study on the bathymetric effects of the Mackenzie River Delta into the Beaufort Sea which lies within our route extent. They found that

landfast sea ice (ice that is aground due to shallow depths of coastline) closely follows the 25 meter isobath provided by the IBCAO. This depth mark is important because the extent of landfast ice dictates the ability of the river delta to discharge into the sea, leading to warm mixing and thereby accelerating sea ice melt (Nghiem et. al., 2014, 877). The inclusion of river discharge into the CESM is key in understanding both sea ice extent, as well as duration of ice cover.

In this study, we plan on operationalizing our bathymetric variable using the maximum potential depth determined by a current Arctic-capable ship. The *Motor Vessel (M/V) Arctic*, operated by Fednav, has been operating throughout the Arctic since its launch in 1978 (Fednav, 2018). Operating both as an oil and ore capable vessel, the *M/V Arctic* provides a base for determining the depth constraints of potential ships traveling along the Northwest Passage. Drafting 15.24 meters (50 feet) under full load, we have decided to add 2 meters (6.6 feet) in order to account for bottom suction, unmarked hazards and the general inaccuracies of current bathymetric surveys (Fednav, 2018).

### *Additional Data Sources*

Land mask data was obtained in vector format from Natural Earth at 1:50m scale, which was suitable for a non-analytical component layer. Sensitive area data was combined from several sources accessible from Canada's Open Government Portal. These datasets included national parks, marine conservation areas, historical and culturally important sites, and natural resource interests (Natural Resources Canada, 1994, 2007, 2017; Parks Canada, 2015).

## *Geospatial Processing*

The strategy and methodology of implementation is displayed in diagram form in Appendix Figures 1 and 2. Further details of GIS processing are detailed in the subsections below. To complete the analyses in this study, ESRI's ArcGIS was utilized.

### *Ice Conditions*

Ice numeral data was processed in MATLAB on its native grid from CESM output SIT and SIC. It was then converted from its native CESM grid to a GeoTIFF through processing in MATLAB. These were provided as five different layers, each representing a different five-year average (2016-2020, 2021-2025, 2026-2030, 2031-2035, 2036-2040) for the month of September. However, the raster resolution (~1 km x 1 km) of IN data did not capture all necessary legs of NWP routes. To solve this problem, the raster data was converted to vector points (1 raster cell to 1 point), with null values (land) selected and deleted by attribute. Subsequently the points were interpolated to raster form by the inverse distance weighting (IDW) method. As a check, the interpolated layer was overlaid with the original IN data to ensure that the layer was not tainted by artificial remnants of the analysis. This check showed almost no discernible changes from the original layer's information. The resulting raster covers waterways that were previously unrepresented by raster resolution, as well as land areas. Although it is not realistic in the physical environment to have sea ice data over land, this consequence of interpolation is masked by land areas. For presentation as a final map, IN data is

displayed categorically as greater than or equal to zero and negative values, which removes the nuances of the climatological conditions, but leaves the primary relevance for marine navigation.

### *Geophysical Data*

Bathymetry data was categorically split into depths that exceeded the minimum safety depth (17.2 m) and depths which were deemed unsafe by a reclassification. Land masks were displayed primarily for aesthetic purposes and were not processed as part of the analysis.

### *Sea Route Data*

Liu et al. (2017) provides a comprehensive composite image of routes from the Arctic Council's *Arctic Marine Shipping Report*, released in 2009, along with a description of the sounds and straits that each leg passes through. We georeferenced this image in ArcMap using notable reference points, which resulted in the route image overlaid onto our map. Using the georeferenced image, we navigated around the land and traced the routes into a new feature class, ultimately resulting in a polyline shapefile of routes. Where the routes were not extended enough on either end, we consulted [www.marinetraffic.com](http://www.marinetraffic.com) to get a general sense of the most heavily trafficked pathways.

### *Final Selection of Routes*

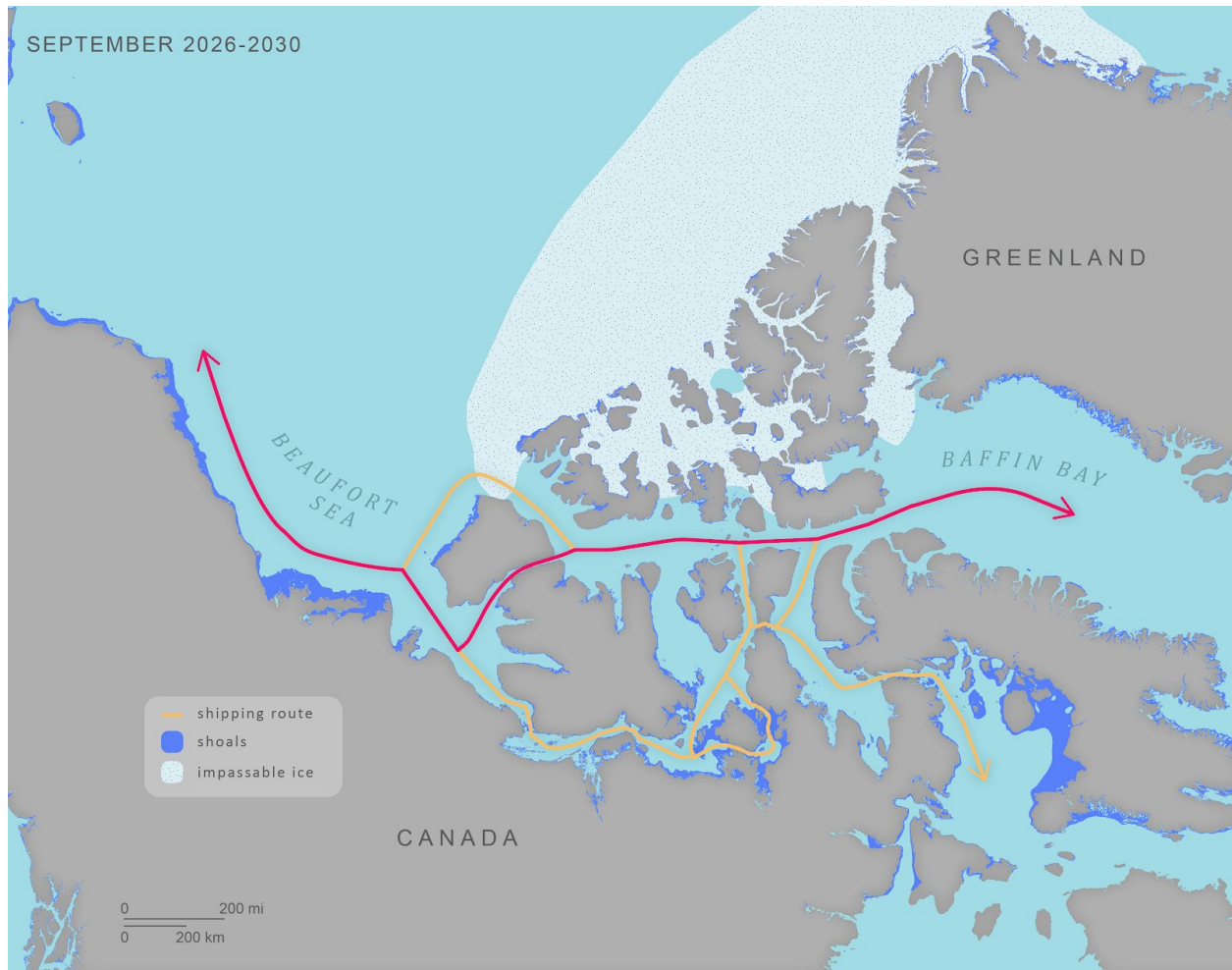
Optimal route selection was able to be completed with the use of the bathymetry layer and the five IN layers. With the routes all in water of a safe depth, the optimal route selected was

the route that was first favorable for the entire transit under climatological average conditions, meaning that the layer of five-year IN averages was positive along an entire route.

## **Results and Discussion**

### *Results*

The first time period where the NWP is passable for a ship of our characteristics (PC6, 15.2 meter draft) is 2026-2030. This means that this is the first period where the average of Septembers is favorable for passage, however, individual years in previous periods may have been passable. During this period, all routes of the NWP were not open. The optimal route, as displayed on Figure 3, is the east to west (or vice versa) passage through the following bodies of water and marine corridors: Baffin Bay, Viscount Melville Sound, Prince of Wales Strait, and the Beaufort Sea.



*Figure 3: Map of NWP routes and September climatological conditions for the period 2026-2030. The route that is open by average conditions for a PC6 vessel has been highlighted in red.*

Vessels with a lesser draft may have found access to a trans-Arctic transit of the NWP in the preceding half-decade (2021-2025), as the Bellot Strait (the passage south of Viscount Melville Sound) was open. However, the depth utilized in our analysis prevented it from being selected as our optimal route.

In the 2031-2035 period average (and remaining in 2036-2040), all sea-routes become open to a PC6 vessel. During this period, optimal route selection becomes a matter of navigation

preference (currents, known hazards, etc...), and actual ice formation. The analysis here presents climatological averages and does not present actual ice conditions existing at certain times.

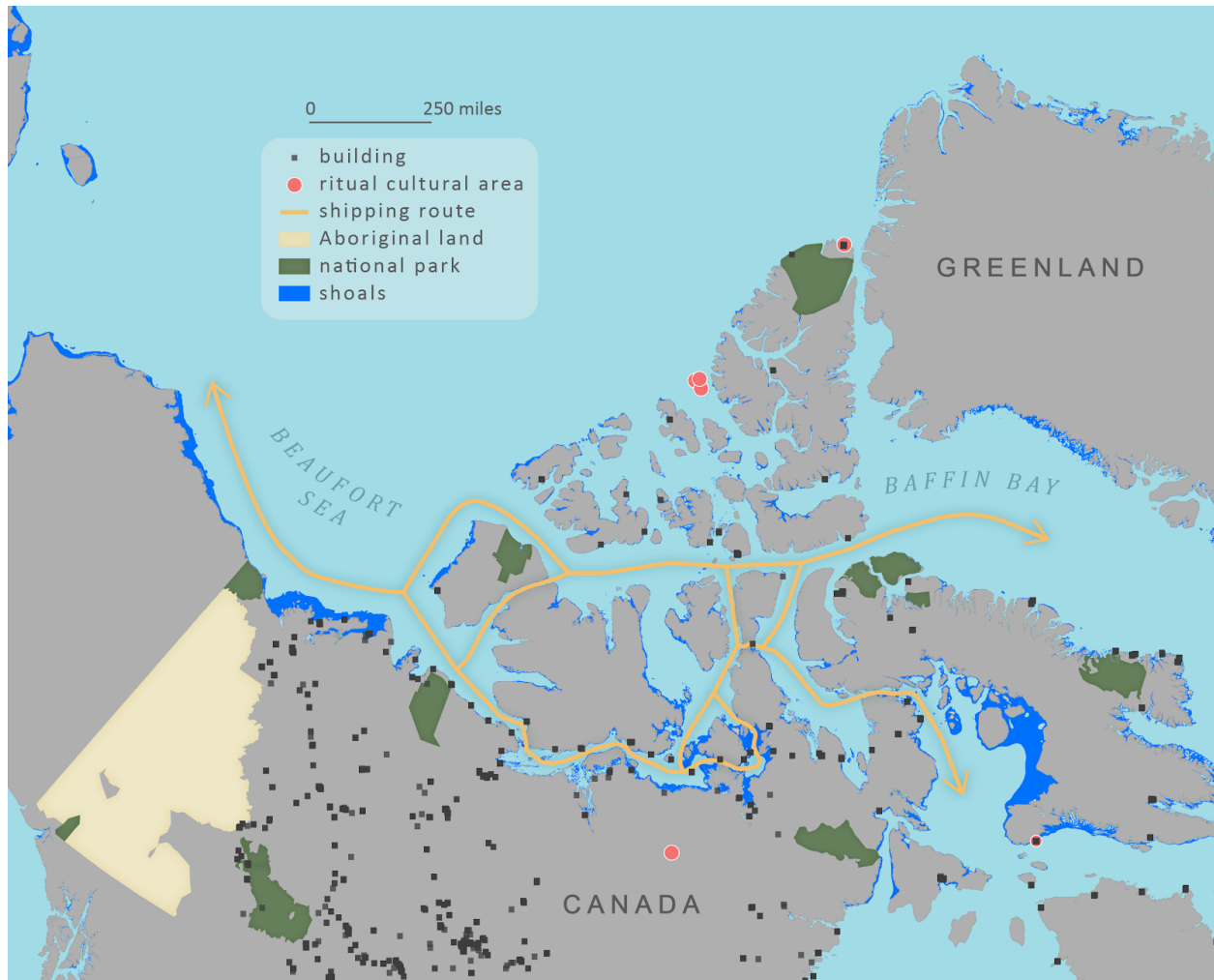
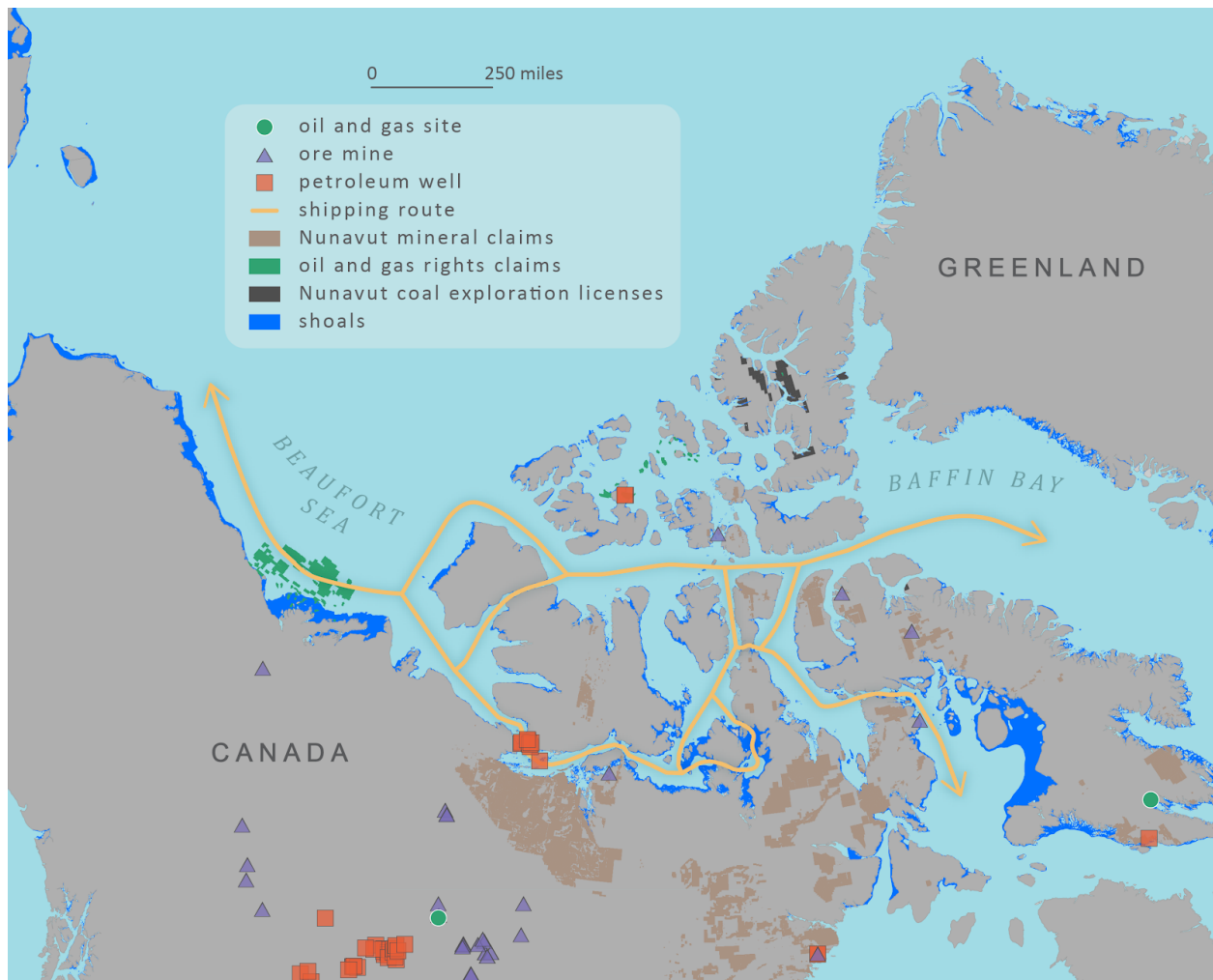


Figure 4: Map displaying sensitive areas of natural, human, historical, and cultural significance.

Figures 4 and 5 display maps of sensitive areas near the NWP. Several of these areas are directly along coastal zones, or encompass the maritime environment. Although the sites in Figure 4 do not directly discourage shipping in the region (although vessel discharge may be

limited in some cases), it puts into perspective the rich depth of human and natural history that must be shared by a growing transportation industry (Ellis and Brigham, 2009). The natural resources available in Figure 5 are indicative of the growing economic interest in the region, outside of pure shipping.



*Figure 5: Areas of known natural resources within the Canadian Arctic. All sites presented here are not utilized equally, if at all.*

## *Discussion*

The IN data utilized here is an average across several different dimensions, and as such many of the nuances of reality that the CESM seeks to model have been smoothed over. Besides the superior performance of the CESM at capturing sea ice, the 40 ensembles of the LENS project make it a desirable datasource. It is important to remember that each of the ensemble members is the CESM's attempt to mimic reality, and that the spread generated is a result of the internal climatic variability. Each ensemble member experiences similar interannual variability as the Earth's climate does, however, this interannual variability is largely lost when treated as an ensemble average. The benefit of the ensemble average is the typical condition that the totality of the individual ensembles points to. In line with this, this study did not consider the individual ensembles, or interannual variability. Additionally, the ensemble means have been treated as five-year averages, which has further smoothed interannual variability. The five years of 40 ensembles mean that each analyzed period is the average of 200 Septembers. When a route has been declared optimal here, it is a reference that the mean state of 40 ensembles over five years are hospitable to shipping.

Bathymetric data used in this study was on the order of 1 km horizontal resolution, which is good for a macroscale analysis, but needs a caveat for navigation. Any uncharted hazards, or shoals not captured by the resolution of the data could be a significant issue for marine usage.

Although this study presents a story of opening sea routes, there are many factors that affect marine transportation in the Arctic. Through the creation of additional maps, sensitive areas were regarded with concern to ship traffic. Existing buildings, national parks, ritual areas,

and aboriginal lands all mark potential liabilities for shipping companies. Oil, gas, and petroleum wells, active ore mines, mineral claims, oil and gas rights claims, as well as existing coal licenses also represent future economic expansion that may affect navigation in the area. As it stands, current sensitive areas are at potential risks from shipping traffic due to the effects of noise and physical pollution. However, these sensitive areas pose little factor in shipping determination, as they limit only discharge from vessels, and not transits all together (Ellis and Brigham, 2009). Potential changes to sea ice variability put pressure on the need for accurate regional predictability. The loss of ice cover is replaced by opening seas that provide for increasing waves and freezing spray, which can quickly reduce a vessel's stability. Transits in winter present the additional challenge of transiting at night, which makes navigation through any ice conditions more dangerous. Additionally, logistical and emergency support for vessels is scarce in the region. Finally, concerned nations (or private companies) are free to charge ice escort fees, which if high enough could offset savings from the shortened distance.

## **Conclusions, Analysis, and Future Research**

### *Summary*

Sea ice thickness and concentration data from a global climate model was analyzed in a GIS environment to determine which routes of the Northwest Passage would first become accessible. NWP legs were found by this study to be increasingly accessible to marine use throughout the early to mid 21st century. For our selected vessel attributes (Polar Class 6 and minimum 56.6 feet navigation depth), this meant a passage was possible beginning in

2026-2030, which expanded to all routes following 2030. There are several sensitive areas within the Arctic, however, these do not currently play a hindrance to transportation.

### *Future Research*

There are several areas for future research to expound on. This study utilized only one emissions scenario, vessel type, and model. Although there is little motivation for utilizing other emissions scenario (especially for relatively short term studies), studies on other vessels could provide interesting and unituitive findings. Climate studies often warrant the use of multiple GCMs to compare performance. Here, it is known that the CESM is one of the better choices for sea ice, but other models may contain pertinent information. The Coupled Model Intercomparison Project (CMIP), an ensemble of multiple climate models, would be a logical choice for follow-on studies. Analyses of other Arctic sea routes, including the Northern Sea Route and the Transpolar Sea Routes could also be considered, which experience their own unique climatic factors that influence the timing of their openings.

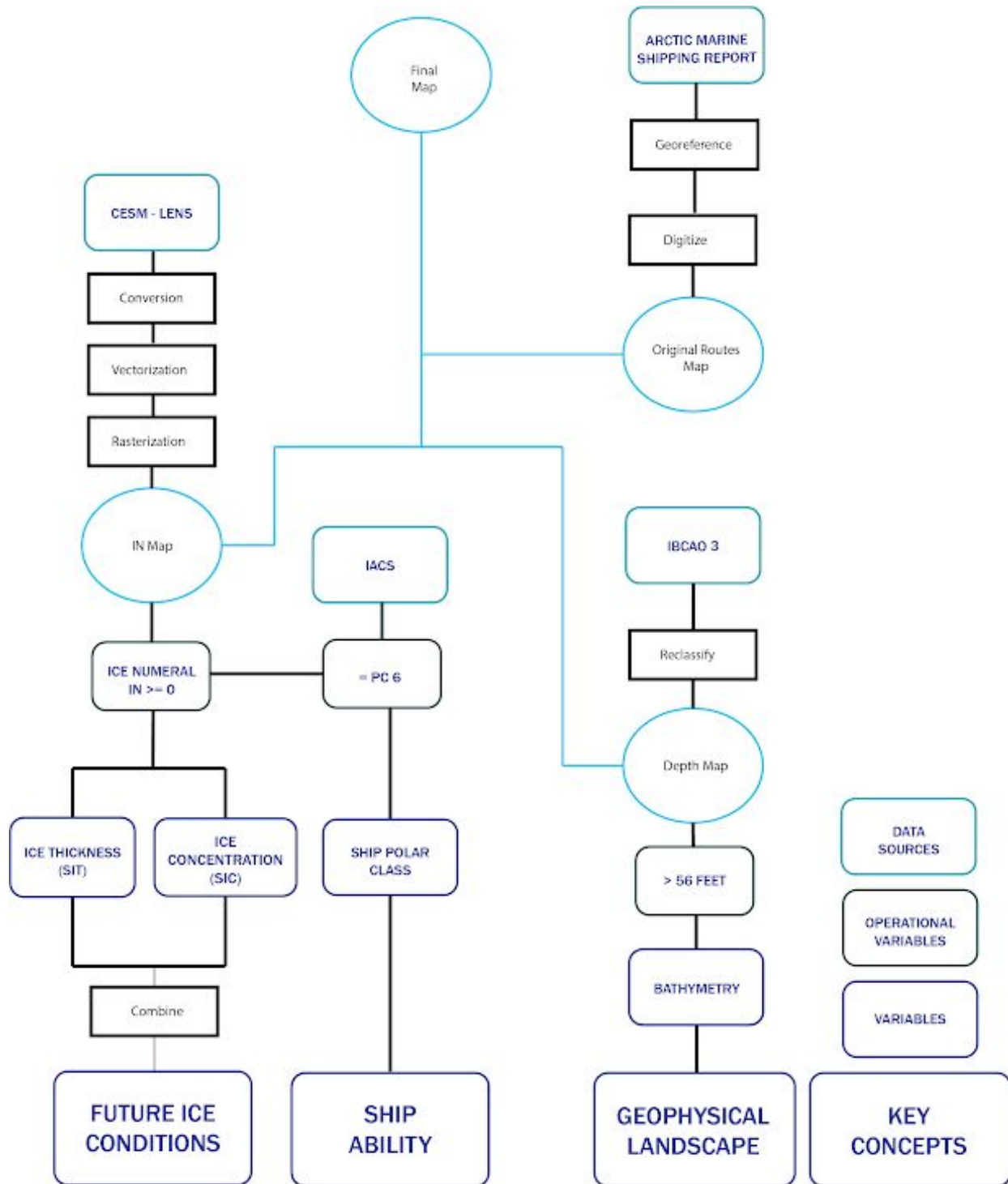
Other areas of future research should also utilize observations. A direct comparison of ship tracks spatial distribution alongside observed ice, sea, and weather data could provide valuable insight into the conditions that are empirically affecting ship transits, which could then be compared to how the IN would have treated those conditions.

## **Appendix**

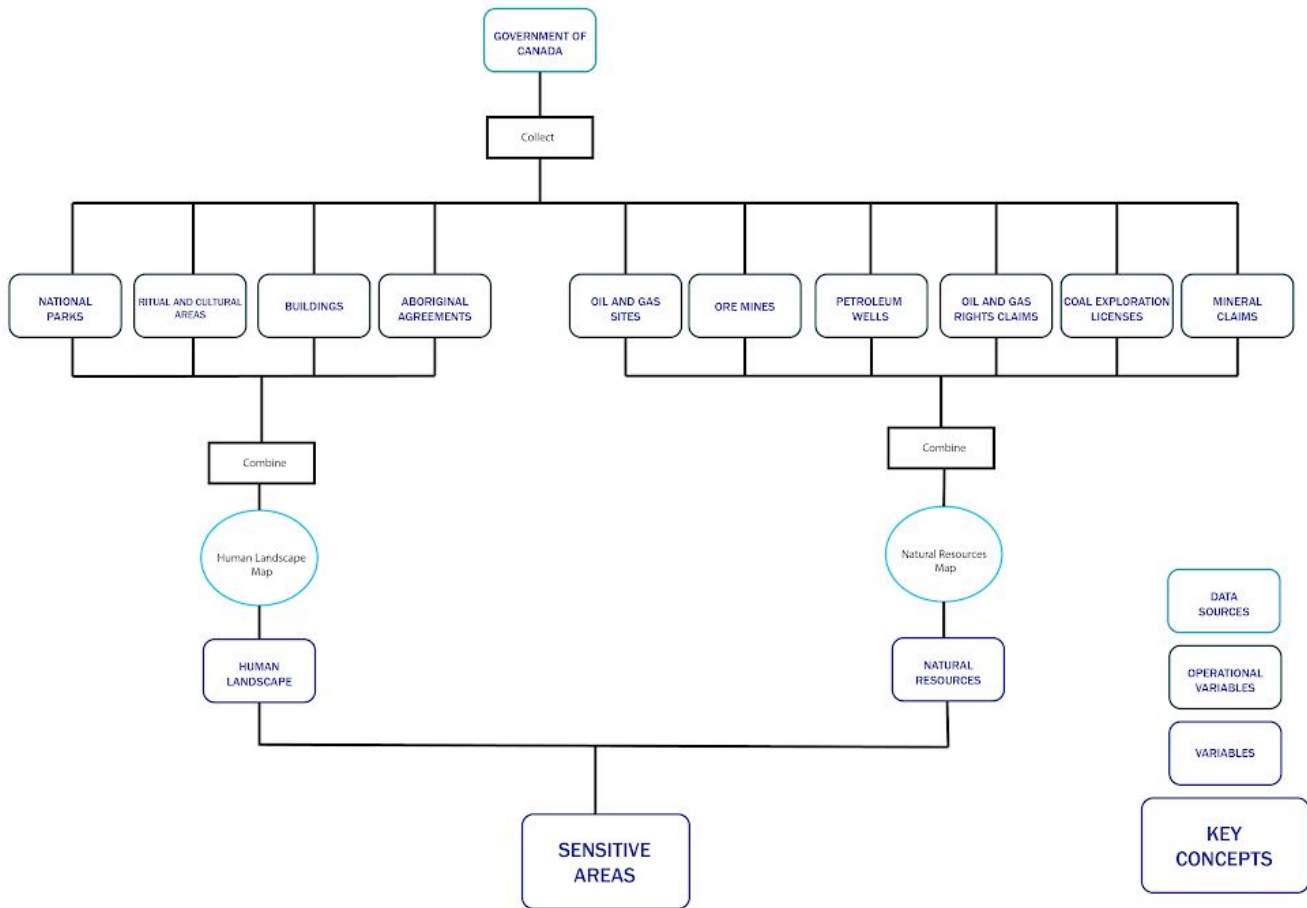
Figure 3 presents the time period with the first passable ice conditions. However, all five 5-year periods were analyzed and displayed as a map for this study. An animation of these five

maps, and the retreating negative IN regime, can be seen here:

<https://drive.google.com/open?id=1qMwNAr9U9D-05YwIqxMV53U2ExJ7csSq>



Appendix Figure 1: Implementation diagram of final analysis, displayed in Figure 3..



Appendix Figure 2: Implementation diagram of supplemental sensitive areas, displayed in Figures 4 and 5.

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