Simulation of maritime paths taking into account ice conditions in the Arctic

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Abstract

As ice conditions evolve in the Arctic and natural resources prices increase, maritime activity in the Arctic is expected to grow within the next few years. Zones of interest across the Arctic are related to human activity mostly to exploit natural resources such as mines, oil and gas, and fish. However, Arctic maritime areas are still dangerous places to cross, requiring specific ice strengthened ships that can navigate in different ice conditions. In this article, we present a simulation tool used to analyse feasible paths between zones of interest depending on ice conditions.

Introduction

Maritime navigation across the Arctic is dangerous and costly due to ice conditions and uncertainty about the bathymetry. Ships navigate in this area only for a specific purpose. This purpose can be to transport goods or people, of to conduct offshore activities (fishing, research, sounding). In this article, we focus on the transport of goods and people, relying on a network of feasible paths between different zones of interest (ZOI). These transit movements are very different from other activity movement such as fishing or conducting soundings.

The first section of this article introduces the zones of interest of the Arctic between which ships are navigating. The second section details the network graph model connecting all the zones of interest. The third section presents the ice model used to establish feasible paths. The fourth section deals with the shortest path analysis on the network taking into account the ice model. The concluding section includes some possible extensions.

Zones of interest

The first step of this analysis is to define the different zones of interest which attract ships in the Arctic. To achieve this task, the Canadian Geographical Name Database was used (Natural Resources Canada 2003). The zones were filtered by: (a) retaining only categories relevant for this study; (b) conducting a buffer analysis to limit selection to geographic locations located close to the shore; (c) performing a geo-visual analysis to select the location categories where ships usually stop. To do so, maritime traffic in the Arctic was overlaid on the shore location map. The maritime traffic dataset was collected by Canadian Coast Guard using the Long-Range Identification and Tracking system (LRIT) for the year 2011 (Hammond *et al.* 2006). The Automatic Identification System (AIS) is another tracking system used to monitor ship position from the shore. In the Canadian Arctic, there is very few AIS base stations able to collect AIS signal from ships navigating in the Arctic (sparse AIS base station network). Satellite AIS has recently been experimented in this area. However, the satellite AIS data source we had access to at the beginning of our study has important temporal gaps that prevent it to be used for a yearlong analysis.

Area of Interest grid network

Once the zone of interest graph is created, a network connecting these ZOI was created using a regular grid mesh for the area of interest. The size of the grid cell must be small enough to allow navigation in sea areas that are practically surrounded by land. Every ZOI of the graph has to be connected to the network and cells are connected to contiguous one by an edge. Using this network, the ZOI can be connected to each other using a shortest path algorithm. The next section presents the modification made to this network in order to take into account the Ice Model.

Ice model

Once the ZOI graph is created, a spatio-temporal analysis of feasible paths between nodes of the graph can be done. Ships can navigate in different types of Sea Ice depending on their Arctic class category. Canadian Arctic Class (CAC) ships range from an icebreaker that can operate anywhere in the Arctic and can proceed through multi-year ice continuously (CAC1), down to CAC4 which would be capable of navigating in any thickness of first-year ice found in the Canadian Arctic. Less capable ships are classified as Type A which can operate in thick first-year ice, through to Type E which can only handle grey ice. The ships types relevant for our study appear across the top of table 1.

The Canadian Ice Services is a government agency that creates Sea Ice Charts for Canadian Arctic area. These sea ice charts use the SIGRID-3 format (Canadian Ice Service 2009) and give information about the location, concentration, stage of development and form of ice. These datasets can be downloaded from the National Snow & Ice Data Center website (nsidc.org). The SIGRID-3 format can give information about ice conditions in a specific geographic area. It can handle three different forms of ice (Fa, Fb, Fc), their stage of development (Sa, Sb, Sc), and their concentration (Ca, Cb, Cc) for each location. For this project, one full year of Sea Ice Charts (2011) was downloaded and integrated into a spatio-temporal database.

A numerical index can be computed in order to know if a ship can navigate into an icy area depending on its form, stage of development and concentration. This index, called the Ice Numeral, is defined in the Arctic Ice Regime Shipping System of Transport Canada (Transport Canada 1998). A ship can navigate in icy areas having a positive Ice Numeral for their ship category (Howell & Yackel 2004, Wilson *et al.* 2004, Somanathan *et al.* 2009). The Ice Numeral (IN) is based on the ice form and concentration, as well as the Ice Multiplier (IM) for each Arctic class category of ship (Table 1). The value of the Ice Multiplier reflects the level of risk or operational constraint that the particular ice type poses to each category of vessel. The two highest ship categories, CAC 1 & CAC 2, are designed for unrestricted navigation in the Canadian Arctic, hence their Ice Multiplier is positive for any Ice Type.

Table 1. Ice Multiplier level of risk that the particular ice type poses to each category of vessel (Transport Canada 1998).

		Ice Multipliers for each Canadian Arctic Ship Category						
Ice Types	**Thickness**	**Type E**	**Type D**	**Type C**	**Type B**	**Type A**	**CAC 4**	**CAC 3**
Old/Multi-Year Ice		**-4**	**-4**	**-4**	**-4**	**-4**	**-3**	**-1**
Second-Year Ice		**-4**	**-4**	**-4**	**-4**	**-3**	**-2**	1
Thick First-Year Ice	> 120 cm	**-3**	**-3**	**-3**	**-2**	**-1**	1	2
Medium First-Year Ice	70-120 cm	**-2**	**-2**	**-2**	**-1**	1	2	2
Thin First-Year Ice	30-70 cm	**-1**	**-1**	**-1**	1	2	2	2
Thin First-Year Ice 2nd stage	50-70 cm	**-1**	**-1**	**-1**	1	2	2	2
Thin First-Year Ice 1st stage	30-50 cm	**-1**	**-1**	1	1	2	2	2
Grey-White Ice	15-30 cm	**-1**	1	1	1	2	2	2
Grey Ice	10-15 cm	1	2	2	2	2	2	2
Nilas, Ice Rind	< 10 cm	2	2	2	2	2	2	2
New Ice	< 10 cm	2	2	2	2	2	2	2
Brash (Ice fragments < 2 m across)		2	2	2	2	2	2	2
Bergy Water		2	2	2	2	2	2	2
Open Water		2	2	2	2	2	2	2

For any ice regime, an Ice Numeral (IN) is given by:

$$IN = (C_a * IM_a) + (C_b * IM_b) + (C_c + IM_c)$$

Where IN is the Ice Numeral, C_a is the concentration in tenths of ice type a, IM_a is the Ice Multiplier (Table 1) for ice type a. Given the Sea Ice Charts for each day in the year 2011, the Ice Numeral can be computed for every available day and Ship Category per grid cell. Then the Ice Numeral values can be aggregated by month for each grid cell in order to get the maximum and minimum values of the Ice Numeral per cell. The maximum and minimum aggregated Ice Numeral values for August 2011 are presented in figure 1 for Type E and CAC 3 ship categories. Green cells indicate that the Ice Numeral is positive, which means that the ship can navigate in this area. The red cells represent a negative Ice Numeral where ship of this category cannot navigate.

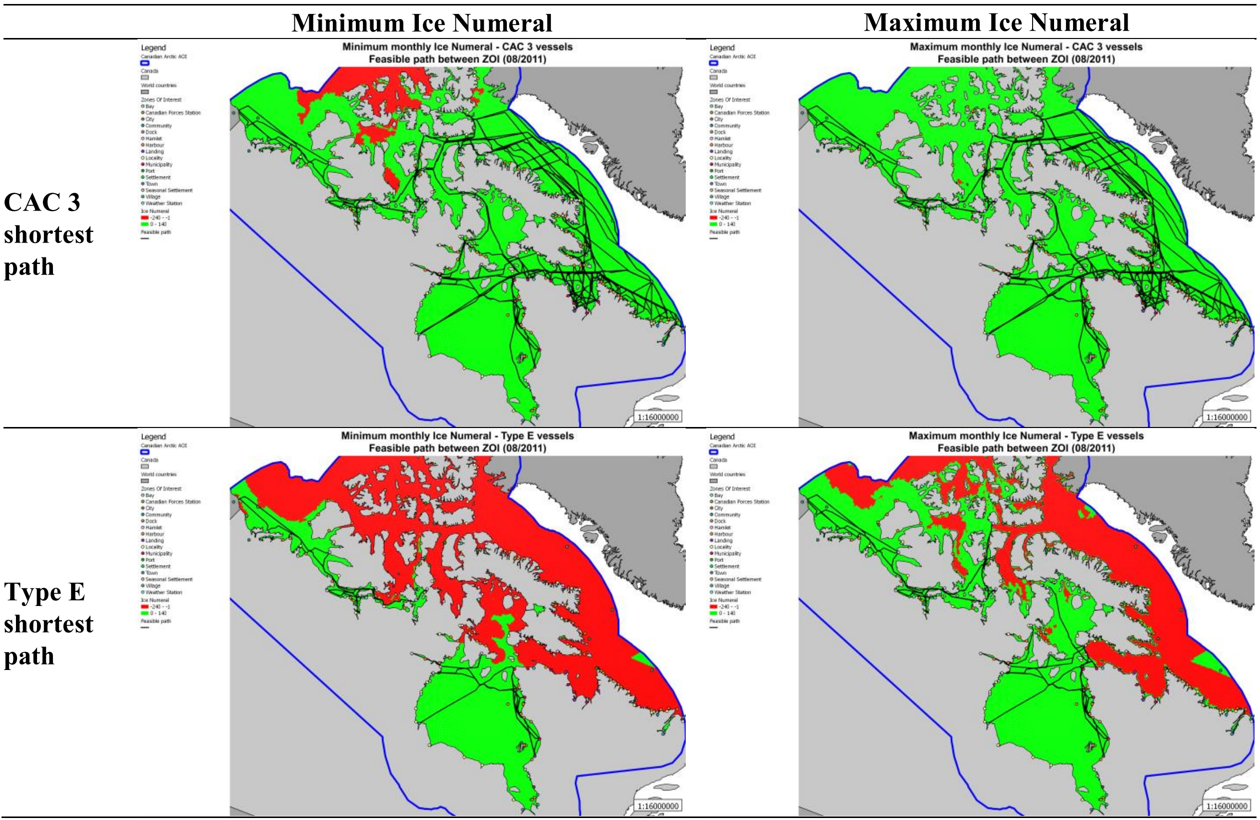

Figure 1. Comparison of monthly aggregated Ice Numerals and feasible shortest path for Type E and CAC 3 ship categories.

Shortest path analysis

The monthly aggregated Ice Numerals can be used to modify the ZOI graph network presented earlier. For each ship category, cells of the network having a negative Ice Numeral are deleted. The new network can then be used to compute a feasible path between two ZOI for every different ship category and every month, using Dijkstra's shortest path algorithm. Shortest paths computed for a Type E and CAC3 vessels in August 2011 have been overlaid in black on Ice Numeral maps in Figure 1.

In some cases, ice conditions can prevent a ship from navigating between two ZOI as the network might be disconnected due to negative Ice Numerals. Ships might have to contour negative Ice Numeral areas in order to reach their destination, or in some cases there is no feasible route at that time of year for a given ship type. The linear distance of the simulated feasible path yields interesting cost evidence on the efficiency and feasibility of the path.

Conclusion

This paper introduced a network model taking into account ice conditions to simulate feasible shipping paths between zones of interest in the Arctic. This analysis is based on the Ice Numeral model to assess if a ship can navigate in specified icy areas. A shortest path analysis based on Dijkstra's algorithm has been proposed. Bathymetry could also be taken into account in order to restrict the graph network depending on ship's draught. As this feasible path simulation relies on sea ice charts, it could be used to simulate future maritime traffic using ice prediction models (Maurette 2010). Moreover, the maximum and minimum ice numerals aggregated for each month can be used as bounds for a statistical analysis on the likelihood of traffic occurring in specified areas.

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