POAC'15
Trondheim, Norway

Proceedings of the 23rd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 14-18, 2015
Trondheim, Norway

COMMON SOLUTIONS AND CHALLENGES TO THE TRAVERSE OF SEA ICE BY SHIPS

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ABSTRACT
The specific challenges of ship operations in sea ice-covered waters of the Arctic depend on factors including the purpose of the operation, the capabilities of the ship and equipment available, the degree of situational awareness and crew experience. Focusing on transits of sea ice in the waters of the Northern Sea Route (NSR), this study demonstrates that the solutions currently employed range from active route finding to accepting getting beset in ice, apparently depending on the purpose of operation. Challenges and operational constraints are discussed. The analysis is based on data provided by the NSR Administration, vessel motion data from satellite-borne receivers of Automatic Identification System signals (S-AIS data of AISSat-1), and sea ice products (AMSR2 ice concentration, ice charts). Travel times northeast of Severnaya Zemlya ranged from 1 to 6 days, depending on ice pressure. A statistical relationship between travel time and ice conditions has been obtained east of the New Siberian Islands. Further insights may be gained by consulting with mariners operating in sea ice-covered waters professionally. Awareness of the actual challenges and preferences of the crew will help guide further research and development in to the most relevant areas.

INTRODUCTION
The Northern Sea Route (NSR) extends from Novaya Zemlya in the west to the Bering Strait in the east and is amongst several regions in the world that see ship traffic in sea ice. Kjerstad (2011) pointed out that combining satellite-based ship position data of the Automatic Identification System (AIS) with ice charts has potential for the analysis of operations in ice-covered waters of the NSR. This study focusses on selected ice-related operational aspects of traverses within the NSR from May 2013 until the end of March 2014.

During the summer season of 2013, the Northern Sea Route Information Office (2013) reported 71 traverses of the NSR or parts thereof in addition to winter-time traffic restricted to the Kara Sea. A detailed analysis of the cargo traffic along the NSR in 2013 has been presented by Humpert (2014), and Buixadé Farréa et al. (2015) discussed other practical challenges of transportation along the NSR.

In general, much can be learned when things do not go smoothly. Taking advantage of large sets of AIS traffic data, automated anomaly detection systems are being developed to identify instances that merit attention (e.g., Martineau and Roy, 2011; Pallotta et al., 2013). These systems are well-suited for high traffic-areas where they can be trained with substantial traffic data. The utility of automated analysis tools along the NSR is limited since the number of cargo transits is comparatively small, significant portions of data are correlated due to convoy traffic, and anomalies due to changing ice conditions are comparatively common. Marchenko (2009) summarized reported ice-induced operational incidents in the Kara Sea area since

1900. She found that “forced drift” was by far the most common reported incident (14 of 29), with other incident types having been “forced overwintering” (7), “ship wreck” (5) and “damage by ice” (3). Among the forced drift events were forced drift in ice jets, and ships becoming beset for weeks to months. While forced overwintering is rarely being reported these days, cargo ships becoming beset in sea ice for short periods of time (hours to days) is still a common occurrence during winter operations in the Baltic Sea, eastern Canada, and, as we will see in the next Section, Kara Sea (e.g., Jalonen et al., 2005; CCG, 2012).

In this study icebreaker escort and icebreaker support are distinguished. The term escort is used to describe a planned journey of a ship with an icebreaker over some extended period of time (typically more than a day), while the term support is used to refer to impromptu help provided by an icebreaker, e.g., breaking free a best ship (taking typically less than a day).

KARA SEA TRAFFIC

Methods

The Northern Sea Route Administration provides excerpts of their ship traffic record online (NSRA, 2014). One daily entry is provided by each ship in the NSR, detailing the state of a ship as per 12:00 Moscow time. Each record includes name, IMO number, location, speed, directions, and a text field with information on destination and estimated time of arrival or related information (e.g. “waiting for icebreaker support”). Ship operators are required to transmit data while in the NSR, and data are entered manually by ship operators, following a standard format. Small inconsistencies or mistakes result in challenges to automated processing, e.g. related to the mixture of character sets (e.g. Russian vs. English look-alike characters), conventions used in different languages (e.g., Russian, English, German), coordinate formats, confusion of east and west longitudes, and mistakes in vessel names or IMO numbers. In order to prepare data for automated processing, we went iteratively through four steps: first, we constructed an automated parser that was able to convert all commonly used formats into a consistent format. Second, we fixed errors in IMO numbers based on the clear text names of the ships provided. Third, we applied heuristic rules for the most common coordinate errors (in particular, confusing E and W close to 180° longitude). Fourth, we plotted the resulting ship tracks and manually looked for obvious errors. Depending on the error, we improved steps 1 to 3, fixed the error manually, or rejected the entry. Occasionally, daily entries were missing (often while presumably at port) or doubled. Deviations in ship reports were more common during the summer season than in winter.

Results and Discussion

We will limit the discussion in this section to traffic between Barents Sea and Kara Sea from 30 November 2013 (arrival of icebreaker Taymyr in the Kara Sea from the East) until 27 March 2014 (Figure 1). 19 ships reported activity in the Kara Sea during this period, three of which were icebreakers (Table 1). All ships had an ice class under the Russian Maritime Register. With the exception of ships with ice class Arc4, the ice class of all cargo ships was at least equivalent to IA Super under the Finnish-Swedish ice class rules.

Nuclear icebreakers Taymyr and Vaygach performed operations mostly out of Port Sabetta (Yamal Peninsula) and Dudinka (Yenisei River), respectively. The only activity of diesel-powered icebreaker Kapitan Kosolapov was to leave the Kara Sea on 13 December, escorting cargo ship Inzhener Trubin along the way. The only apparent convoy was an icebreaker escort of cargo ship S Kuznetsov and tug Nord, leaving Sabetta Port on 24 December. Traffic through the Kara Strait south of Novaya Zemlya dominated, with only 9 journeys around Cape Zhelaniya at the northern tip of Novaya Zemlya. Of those 9 journeys, only Enisey and Ivan Ryabov made one unassisted traverse each. The remaining 7 journeys were escorted by icebreakers. Destinations in the Kara Sea were either the port of Dudinka for natural resource transport and supply operations, or Sabetta Port for supply operations.

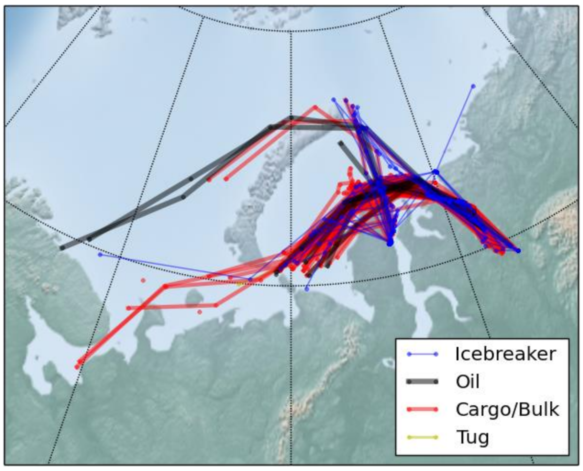

Figure 1. Overview NSR Administration data from 30 Nov 2013 until 27 Mar 2014.

We found that ship operations in the Kara Sea in winter can be classified into four groups (Table 1):

1. icebreaker services,
2. ships travelling under icebreaker escort,
3. ships travelling unescorted but receiving icebreaker support as needed, and
4. ships travelling unescorted and not requiring icebreaker support.

Ships of group 1 were essentially limited to nuclear-powered icebreakers with the only diesel-powered icebreaker having left early in the season (in December). Ships of group 4 were without exception double-acting, specifically of Norilskiy Nickel-type operated by Arctic Express. They were designed with icebreaking capability and we did not find indication that they received icebreaker support. Most other ships fell into group 2, i.e. they were escorted by an icebreaker through the Kara Sea.

The most remarkable mode of operation was that of ships in group 3 (Ivan Ryabov and Inzhener Veshnyakov): unassisted traverse of the ice, getting beset, waiting for support from an icebreaker nearby, and continued unassisted traverse (possibly getting beset again). Ivan Ryabov made three unescorted journeys to or from Sabetta, passing the Kara Strait on 18 Dec and 20 Jan, and Cape Zhelaniya on 18 Mar. Two were apparently uneventful. However, after passing Kara Strait on 18 Dec, Ivan Ryabov reported to be drifting from 19 to 22 Dec (near Kara Strait), 24 to 28 Dec (north-west of Bely Island), and 29 to 30 Dec (north of the Gulf of Ob). In each case, Taymyr came to support. Inzhener Veshnyakov made only one traverse to Sabetta. Entering through the Kara Strait on 30 Nov with an expected date of arrival in Sabetta on 2 Dec, she was not able to pass the area north-west of Bely Island on her own accord and reported to be waiting for ice support from 1 until 6 Dec, then reported to be drifting until Taymyr broke her free on 8 Dec. After moving at 6 knots on 9 Dec, she reported again to be drifting from 10 to 19 Dec, still in the same area. On 20 Dec she went back south-west toward the ice edge, waited for Taymyr drifting from 21 until 22 Dec, and reached Sabetta escorted on 24 Dec, three weeks later than planned.

Table 1. Ships active in Kara Sea between 30 Nov 2013 and 28 Mar 2014 with IMO number, name, vessel type, ice class according to the Russian Maritime Register, route taken in or out of the Kara Sea (North or South), and type of operations.

IMO	Name	Type	Class	Route	Type of Operations
8417481	TAYMYR	Nuclear icebreaker	LL2		escort and support
8417493	VAYGACH	Nuclear icebreaker	LL2		operations
7406320	KAPITAN KOSOLAPOV	Diesel-powered icebreaker	LL4	S	
8502080	INZHENER TRUBIN	General cargo	UL	S	navigation under
8624515	NORD	Tug	LL4	S	icebreaker escort
9210359	S KUZNETSOV	General cargo	Arc4	S	
7721237	ALEKSANDR SUVOROV	Bulk carrier	Arc4	N	
8131934	VIKTOR TKACHYOV	Bulk carrier	UL	S	
7421942	INDIGA	Crude oil tanker	UL	N	
8131893	PAVEL VAVILOV	Bulk carrier	Arc4	N & S	
8406705	YURIY ARSHENEVSKIY	Ro-Ro cargo	Arc7	N & S	
7942348	IVAN RYABOV	General cargo	UL	N & S	unassisted, received
8502107	INZHENER VESHNYAKOV	General cargo	UL	S	icebreaker support
9330836	NORILSKIY NICKEL	General cargo	Arc7	S	unassisted operations,
9404015	MONCHEGORSK	General cargo	Arc7	S	double-acting ships
9404027	ZAPOLYARNYY	General cargo	Arc7	S	(all ships are of
9404039	TALNAKH	General cargo	Arc7	S	Norilskiy Nickel-type)
9404041	NADEZHDA	General cargo	Arc7	S	
9585273	ENISEY	Oil/chemical tanker	Arc7	N & S	

NSR TRANSECTS

Methods

To track ship traffic in remote areas, data can be used of satellite-based receivers for messages of the automatic identification system. The Automatic Identification System (AIS) has been developed for collision avoidance of ships at sea. Ships receive and broadcast messages in the VHF band, including identification information, location, speed, and direction. Messages are broadcast every 2 to 30 seconds, depending on the state of operation of a ship. Although designed for line-of-sight operations at sea (i.e., typically limited to a range of 74 km), messages can be detected by satellite-based receivers (S-AIS) in low Earth orbit (Eriksen et al., 2010). S-AIS allows for ship traffic monitoring within the wide field of view of the satellite, including remote regions. However, S-AIS data are not perfect. Relying on a protocol designed for local operations, message concurrency leads to data loss, comparatively low signal-to-noise ratio leads to message errors that the protocol cannot detect, and the moving field of view of the satellite leads to systematic data gaps that can exceed 6 hours, depending on the region, for a single satellite.

We used S-AIS data of the polar-orbiting Norwegian satellite AISSat-1 to analyze ship traffic along the Northern Sea Route (NSR) (Eriksen et al., 2006; 2010). Compared to data of interest in this study, the volume of data is tremendous: while only larger ships are required have AIS transmitters on-board, AIS is also used by many small ships, including river traffic. In addition, open-water and coastal traffic greatly exceed ice-related traffic of interest here. Due to technical constraints mentioned above, data on individual ships are available at irregular intervals, including short periods of time with data every 2 seconds and data gaps of

1 to 6 hours. We reduced data volume to at most one message per hour per ship. Although messages were generated automatically, data quality had to be ensured manually. Issues include a few operators entering a wrong identification number (MMSI) into the radio or using the manufacturer's default setting, some radios reporting the location as North Pole in the absence of a GPS location fix, and transmission errors of location or MMSI that cannot be detected by the AIS protocol. As a result, S-AIS data pre-processing is similar in complexity to pre-processing of data from the Northern Sea Route Administration and manual verification is crucial. In this study, data presentation is limited to ships with IMO number.

For further analysis, ship tracks were superimposed on Russian ice charts, and AMSR2 sea ice concentration data were extracted along the respective ship tracks (Spreen et al., 2008). Ice concentration is the most readily accessible parameter and at the same time highly relevant. For example, in a multiparametric study of the dependence of ship speed on modeled ice conditions in the Baltic Sea, Löptien and Axell (2014) found significant correlations with ice concentration, level ice thickness, ridge density, and drift speed and direction. Of these, ship speed correlated highest with ice concentration. Correlations with simulated ice convergence were found to be statistically not significant. Other parameters that are important include ice type, state of deformation, floe size, and in particular ice pressure.

Results and Discussion

The discussion in this section is limited to traffic in the NSR from 15 May 2013 (traffic started to extend beyond the Kara Sea) until 30 November 2013 (NSR traffic limited to Kara Sea). Ice-bound traffic beyond the Kara Sea started with preparations for the rescue operation of North Pole drifting station NP-40 in May 2013. However, commercial activity did not start until the end of June.

Example of a journey

Figure 2 gives an example of a traverse along the Northern Sea Route. In this particular example, Marinor traversed the NSR from east to west in August. Marinor entered the Kara Sea north of Novaya Zemlya unescorted at speeds above 10 knots until she met ice and had to anchor for three days. During this time she reported to be "waiting for icebreaker assistance" and adjusted her expected departure from the NSR forward. Receiving icebreaker escort through the archipelago of Severnaya Zemlya, she continued to traverse the Laptev Sea in an icebreaker convoy though waters that AMSR2 indicates were ice-free. She circumnavigated the East Siberian Islands to the north in a smaller convoy consisting of herself and icebreaker Vaygach. AMSR2 data suggest that they encountered ice on 24 August, at a point where they turned sharp east. They headed toward the coast near Pevek, visited Wrangell Island briefly, and separated at 170° W from where on Marinor continued herself through open waters. She was traveling at or above 10 knots with the exception of periods where AMSR2 indicated the presence of sea ice. Note occasional data gaps in this figure, which are quite typical for S-AIS data.

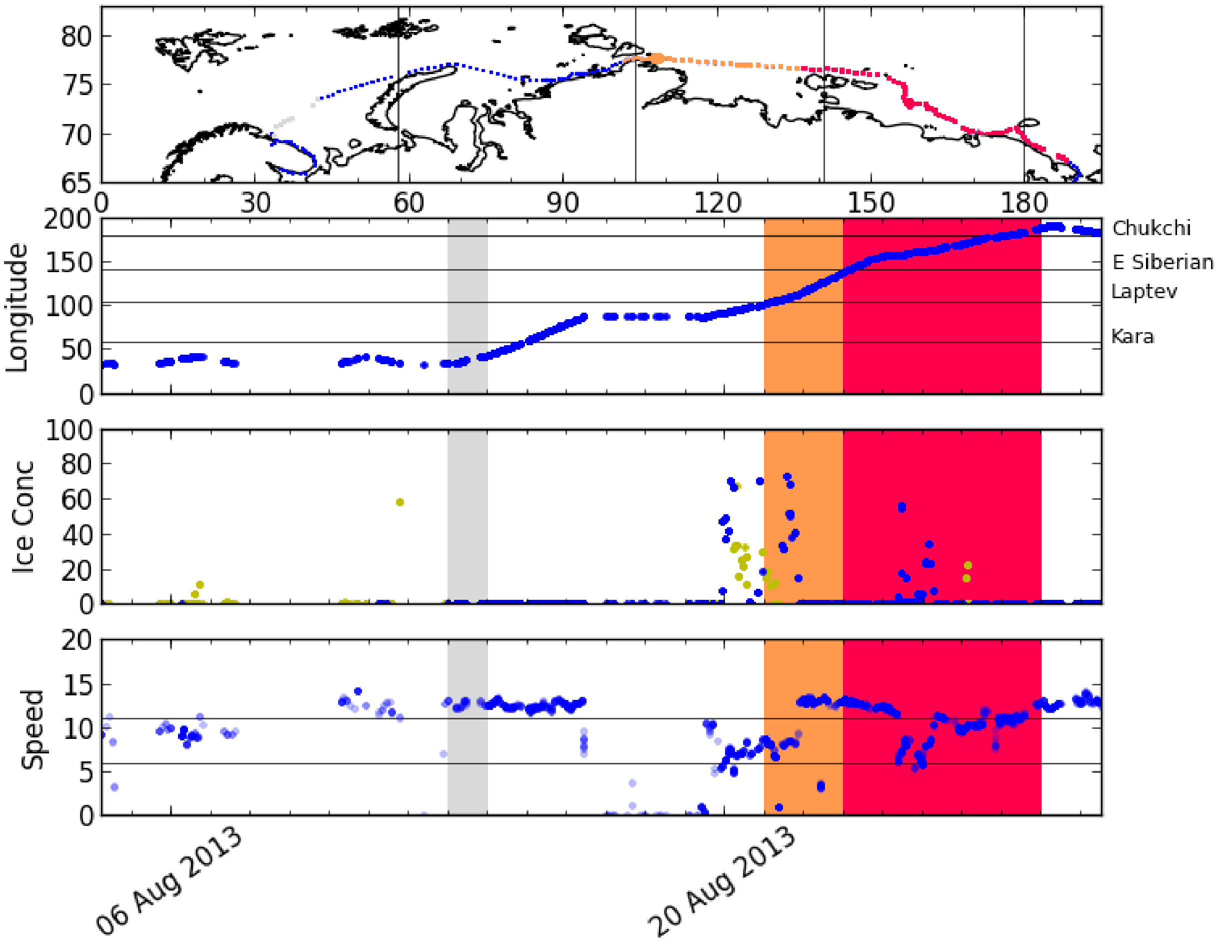

Figure 2. East-to-west transit of the NSR of Marinor in August 2013. The upper panel shows a map with track for reference, the lower three panels are timelines of longitude (degrees East of 0°), ice concentration from AMSR2 data, and reported ship speed. Gray, orange, and red background colors indicate periods of convoy without icebreaker, with icebreaker escort and at least one other ship, and only with icebreaker escort, respectively. Larger dots in map near Severnaya Zemlya and the East Siberian Islands indicate ice encounters. Ice concentrations shown with yellow dots are nearest to land and may therefore be overestimated.

Pressured ice at Severnaya Zemlya

The first navigation of the NSR in 2013 was performed by oil tankers Indiga and Varzuga (both ice class UL), escorted by icebreaker Vaygach. The convoy passed through the ice at the northern tip of Severnaya Zemlya on 1 July 2013 at about 5 knots and sailed down the east coast of the archipelago in mostly open waters above 10 knots (Figure 3). After passing through ice in the Laptev and East Siberian Seas, they reached Pevek on 10 July. On 5 July, Nordic Orion (DNV ice class ICE-1A), escorted by Taymyr, attempted to repeat the northern passage of Severnaya Zemlya (Figure 3). However, winds had changed, pressurizing the ice along the east coast of the archipelago. Options for ice management were limited with the nominal beam of Nordic Orion 3.4 m wider than Taymyr. Progress was slow at 1 to 2 knots until 11 July when they approached more open ice and were joined by icebreaker Yamal to assist. They passed Peverk on 21 July. Due to pressured ice, the Taymyr escort took six days starting 5 July to traverse essentially the same stretch the Vaygach escort traversed in one day on 1 July.

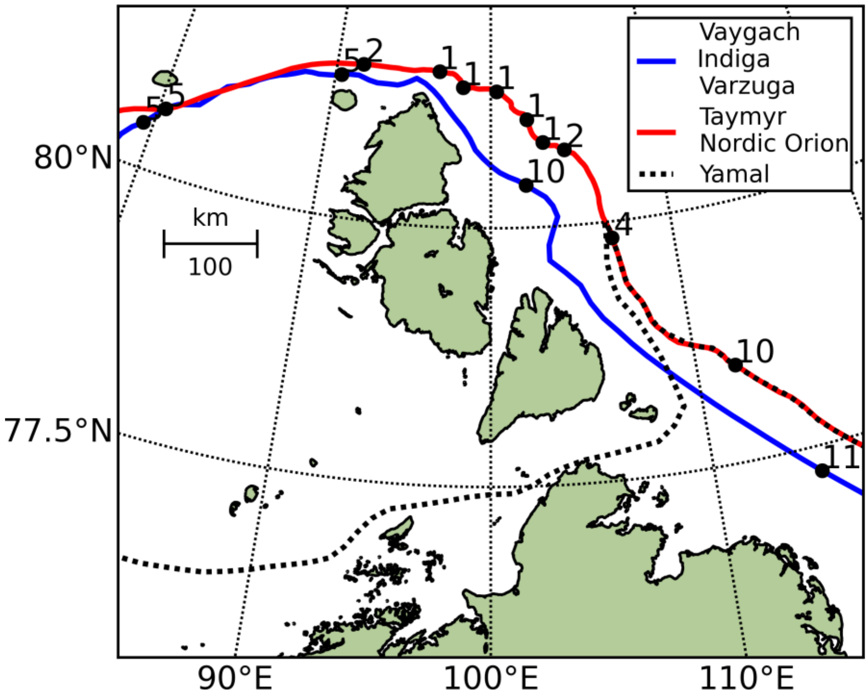

Figure 3. Eastbound ship tracks around Severnaya Zemlya of Vaygach escorting Indiga and Varzuga (blue line, north of Severnaya Zemlya on 1 July 2013), and Taymyr escorting Nordic Orion (red line, north of Severnaya Zemlya on 5 July 2013). Markers indicate midnight UTC of any given day, labels show the average speed of that day in knots. The dotted line shows the track of Yamal, meeting Taymyr and Nordic Orion at the end of 11 July 2013.

Once the northern route had been chosen and ice conditions became unfavorable there was little that could be done until ice conditions eased. Given the vast distances and associated travel times, short term forecasts may have helped finding a more pleasant place to wait for more favorable ice conditions, reducing fuel consumption and potential for damage to the ship.

Route choices at the New Siberian Islands

Figure 4 shows S-AIS waypoints of 2013 in the area around the East Siberian Sea. We counted 94 passages of the East Siberian Islands at 142° E, made by 43 different ships (not including Viktor Buynitskiy who did not enter the East Siberian Sea but whose destination were various East Siberian Islands), of which 24 passages were made by 6 different icebreakers. Of the non-icebreaker passages, 24, 42, and 4 took place north of Novaya Sibir, through Sannikov Strait, and through the coastal shallow waters of Laptev Strait, respectively. Icebreakers used the northern route and Sannikov Strait 9 and 15 times, respectively.

Navigation around and through the East Siberian Islands followed bathymetry: close to land, yet in deep enough waters. While traffic through the straits is necessarily spatially concentrated, the consistency of the northern route east of the East Siberian Islands is striking. The northern route was in use from 5 July until 23 October, except for the period from 1 to 28 September. Russian ice charts suggest that this section had a navigable ice concentration of 1/10 to 6/10 in August and October. Use of Sannikov Strait started on 17 Aug after the strait had cleared of ice, and ended with the westward journey of Taymyr on 28 Nov.

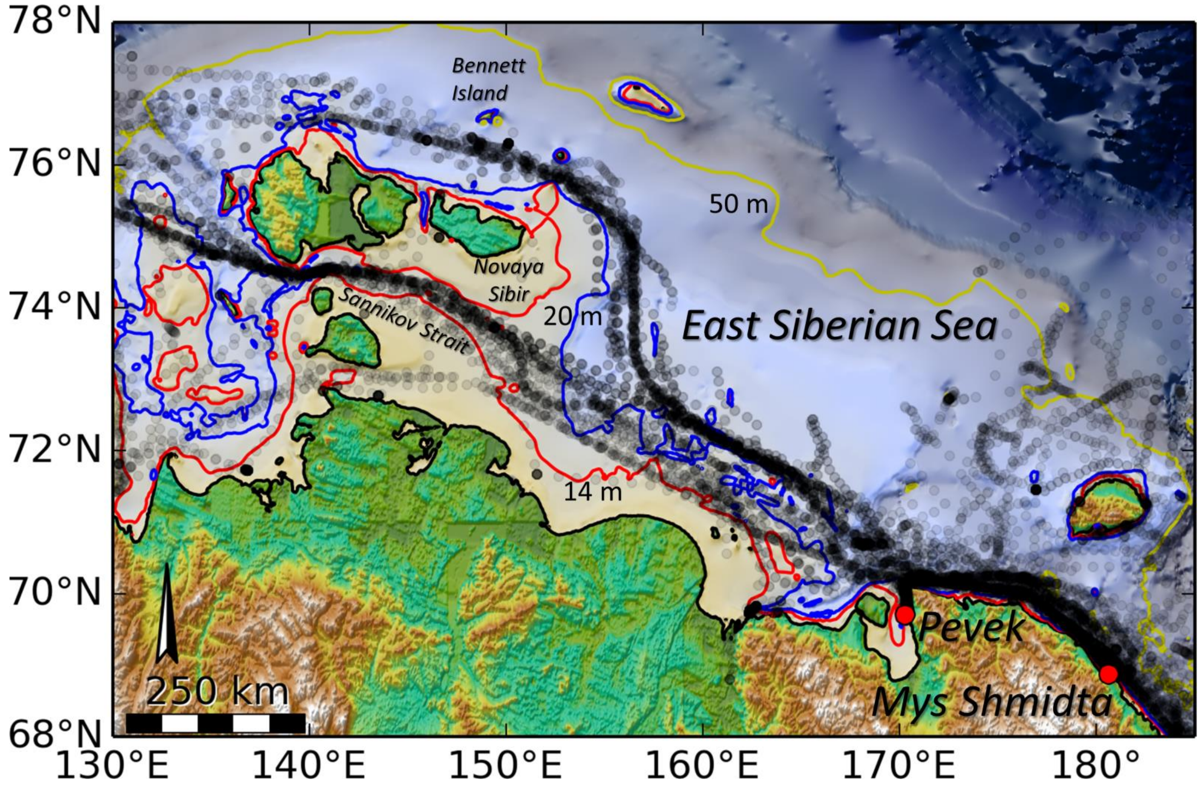

Figure 4. S-AIS way points around the New Siberian Islands (142° E) and in the East Siberian Sea in 2013. Note that no more than one waypoint per hour is shown.

For the following analyses we interpolated ship tracks onto regular 1-hour intervals. Since sea ice was often encountered during journeys along the northern route, we investigated those journeys in more detail. Travel times between longitude 150° E and 160° E were calculated (only for journeys passing 75.5° N) and related to time of year (Figure 5) and average ice concentration (Figure 6). As one would expect, the travel time shows a tendency to decrease from July to August (Figure 5). The northern route had not been taken during much of September even though the route was ice free at that time. It appears as though there is a trend towards increased journey length again in October. Mari Ugland took particularly long time due to maneuvers north of the East Siberian Islands and should not be considered in this context.

We related travel time to average sea ice concentration along the respective paths taken based on AMSR2 sea ice concentration data (Spreen et al., 2008). The scatter plot in Figure 6 shows a clear trend of increasing travel time with ice concentration. In particular, travel times at high ice concentrations (e.g., NS Yakutia, Nordic Odyssey) were 3 times longer than the shortest travel time in open water (Yong Sheng). Travel times of the Russian nuclear icebreakers and the Finnish icebreaker Nordica (DNV ice class POLAR-10) appear to not correlate with ice concentration outside of escorts, which is probably largely explained by their ice class.

Investigating ship tracks in more detail in the area leads to additional anecdotal insight into operations (Figure 7). Of particular interest are deviations from normal. Ship tracks spread over 100 km in East-West direction, while the spread of the "normal" track is only 10 km at 156.5° E. "Wiggles" along most paths could be signs of maneuvers to avoid heavy ice.

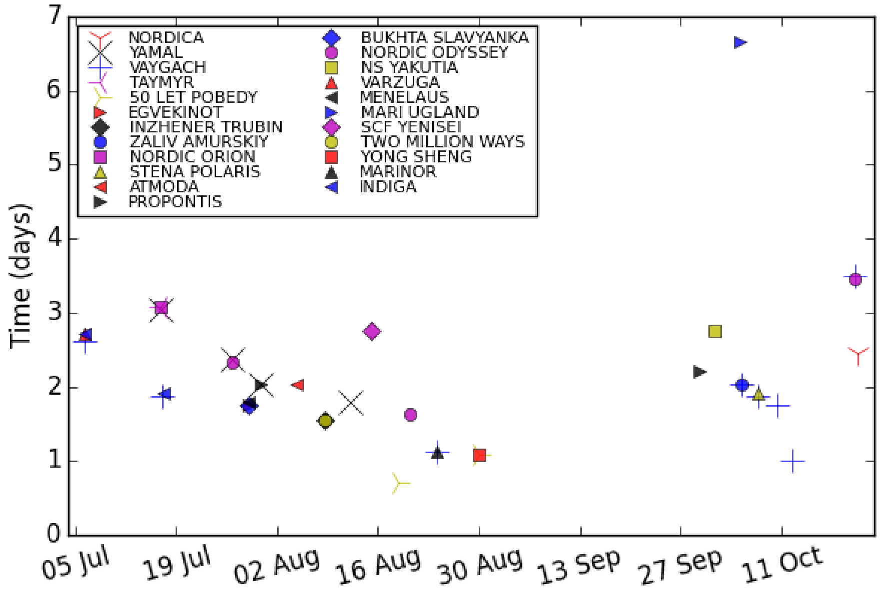

Figure 5. Travel times along the northern route around the East Siberian Islands, between latitudes 150° E and 160° E, depending of day of year in 2013.

Further:

- The escorted eastbound convoy of Varzuga and Indiga on 6 Jul shows an eastward deviation to 158.5° E at 74° N. Russian ice charts indicated pockets of lower ice concentration in the area at this time, making it likely that the convoy followed a path of favorable ice conditions.
- On their westbound journey on 29 Jul, the unescorted triple-convoy of Bukhata Slavyanka, Menelaus, and Egvekinot chose a route that is more to the west (154.5° E) than the path escorted by icebreakers at the time (156.5° E). Russian ice charts show 7/10 to 10/10 ice concentration in the entire region while AMSR2 data suggest that the convoy went through ice concentrations <5/10. Hence, it is possible that the convoy found a route through favorable ice conditions.
- The unorthodox "shortcut" taken by Atmoda on 4 Aug lined up with an area of 1/10 to 6/10 ice concentration on the Russian ice charts. This transit happened during a transition period from consistently heavier ice condition to increasing areas of lower ice concentration.
- Escorted, Norwegian-flagged Marinor kept a more northern course on her eastbound journey from 24 Aug onward (passing 159° E above 73° N). Based on comparison with Russian ice charts, the ships turned hard east when they encountered a pocket of ice with high concentration 7/10 to 10/10.
- From 29 Sept until 8 Oct there were a number of ships taking a course with a distinct west-dent to 155.5° E at 74° N (e.g., the track of NS Yakutia on 2 Oct is easily seen in Figure 7). Comparison with Russian ice charts suggests that ships followed a path through 1/10 to 6/10 ice concentrations, flanked by heavier ice conditions to the east and young ice in shallower waters to the west.
- Nordic Odyssey took a somewhat unusual path on 20 Oct. Heading west through new ice, she waited for more than 12h at 72.5° N, 155° E before turning north and meeting icebreaker Vaygach. The reason for this is not clear to us. Possibilities include a change of plans in the light of ice conditions and a delayed icebreaker.

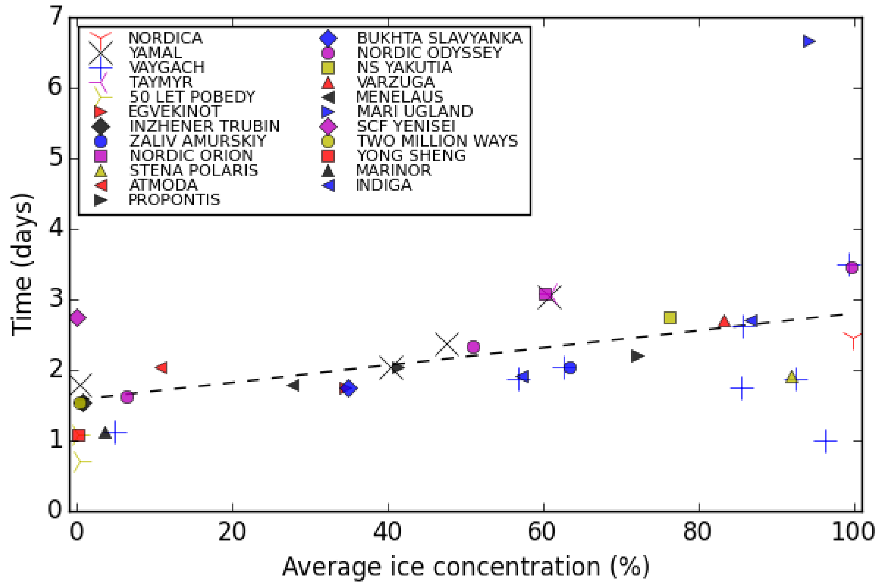

Figure 6. Travel times along the northern route around the East Siberian Islands, between longitudes 150° E and 160° E, depending on average ice concentration from AMSR2 data. The trend line does not consider icebreakers (Nordica, Yamal, Vaygach, Taymyr, 50 Let Pobedy) and Mari Ugland. The trend line follows *time*=1.6 days + *concentration* * 1.2 days.

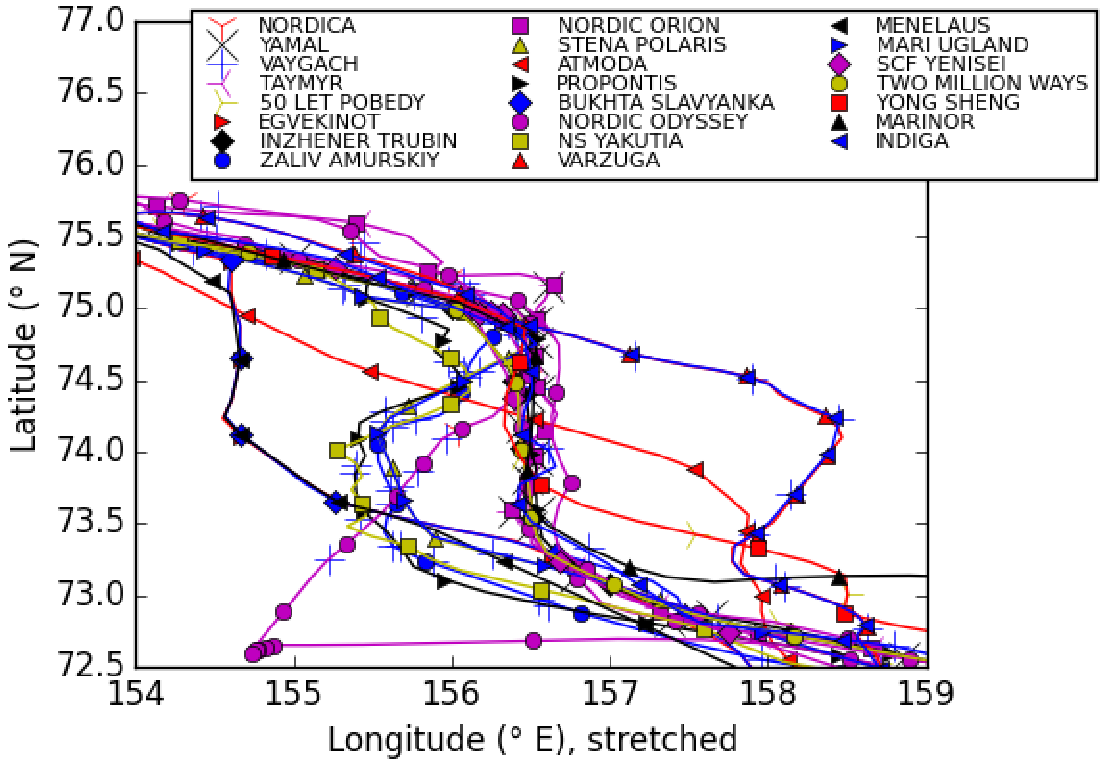

Figure 7. Ship tracks with markers shown every 4 hours. Icebreakers are marked only during escorts. Note that the map is stretched in East–West direction by a factor 4. 1° in longitude is 30 km at 74° N.

SUMMARY AND CONCLUSIONS

There is clear potential in analyzing ship operations from traffic logs (NSRA, 2014), S-AIS data and sea ice coverage products. Statistical results can be obtained (Figure 6), and further insights can be gained from case-by-case analysis of track histories (Figure 7). The statistical analysis was based on coarse resolution sea ice concentration, accounting only implicitly for any fine structure (e.g., leads), operational preferences of the mariners (e.g., safest vs. fastest route), and ice breaker escorts. Hence, one would expect such relationships to depend on location at the very least. Automated data quality assessment of ship track data is required to for analysis of high traffic areas or extended periods of time. Focusing on three regions in the NSR (Kara Sea, northern circumnavigation of Severnaya Zemlya and the New Siberian Islands), we noted the following with relevance to operations in sea ice:

- In unescorted operation, current technology allows the construction of cargo ships that master sea ice conditions that cause older ships to become beset.
- Sending an unescorted ship into winter sea ice while accepting the risk of it becoming beset for days at a time seems to be an acceptable mode of operation where delivery is not time-critical.
- Sea ice under pressure can force a cargo ship escorted by a nuclear icebreaker to essentially come to a stand-still.
- Icebreaker escorts depend on synchronization of travel schedules, and waiting for icebreakers may be required.
- Statistically, travel time increases with average sea ice concentration along the way. This statistical relationship holds even for escorted journeys.
- Ships, escorted or not, deviate from established routes to seek out paths of favorable sea ice conditions.

It appears that sea ice products and forecasts for routing would be useful along the NSR, for energy efficient navigation and safe and economic operations in sea ice-covered waters (e.g., Kotovirta et al., 2009; Choi et al., 2015). Ice properties may be derived from local observations, remote sensing, or reanalysis products (e.g., Petrich and Bonath, 2014) and should improve the forecasts. While we were not able to determine the most useful parameters to forecast in this study, it was obvious that ice pressure and ice concentration in particular of thick ice influenced progress, choice of route, and need for an icebreaker escort. Floe size data were not available for comparison. However, deeper insights may be gained from discussions with master mariners navigating ice-covered waters professionally. While we chose a few examples of navigation away from land masses, it may also be insightful to analyze traffic through straits.

ACKNOWLEDGEMENTS

This study was inspired by the network on Safe and Economic Operations in Seasonally Sea Ice-Covered Waters (OpSIce), supported by the Norwegian Ministry of Foreign Affairs project number RER-13/0041. Work was supported by the Research Council of Norway project number 195153 (ColdTech) and industry partners. The Norwegian Coastal Administration kindly provided S-AIS data. Daily vessel records were provided by the Northern Sea Route Administration of the Ministry of Transport of the Russian Federation. AMSR2 sea ice concentration data were provided by University of Bremen. The comments of the anonymous reviewer are appreciated.

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