Kiel, October 25th
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Dear Hajo Eiken,

we uploaded a revised version of our manuscript "Ice and AIS: ship speed data and sea ice forecasts in the Baltic Sea” and included the suggestions of the reviewers. All changes in the text are marked in bold in the accompanying pdf-file below. Particularly, we added three new Figures, to evaluate the sea ice model and to illustrate the ice dynamics in the regions of interest. Detailed answers to the comments of both reviewers follow below.

Yours Sincerely, the authors

Answers to the reviewers:

Reviewer #1 (Anders Omstedt):

The author’s compares ship speed based on AIS calculations with forecasted ice information and particularly ice drift, ice concentration and ice thickness. The paper is interesting as AIS provides a new data source with high resolution data and for the studied region a clear connection between AIS calculated ship speeds and sever ice conditions can be found. The relation to modeled ice drift data is not clear. I miss a discussion about the dynamics in the test region. The authors have used the Northern Bothnian Sea and the Northern Kvark Strait as test area. This area is well known to be very dynamic with strong currents through the Strait (Green et al., 2006). Most 3D models have not addressed the dynamics in the Northern Kvark Strait and we get no information in the paper if HIROMB can model the currents realistically in this region? The problem with modeling ice drift in connection to land fast ice is mentioned as a possible problem but has not been evaluated in the present article. Ice drift in shallow channels open also up problems related to modeling the ice rheology and here a standard Hibler approach developed for large scale ice dynamics will have problems. Will the ice floes at high ice concentrations pass the Northern Kvark Strait or will it jam?
Direct observations on ice drift through the test region and in particularly the Northern Kvark Strait are therefore needed. The comparison between observed and modeled ice drift data needs more studies before it should be used in relation to AIS. I therefore recommend the authors to include a discussion on the ice and the current dynamics in the test region and introduce a section where HIROMB ice drift is compared with observations in the test region. An alternative approach could be to discuss the ice and

current dynamics in the region and neglect the present part related to modeled ice drift.

References Green, M.,J.,A., Liljebladh, B., and A., Omstedt (2006). Physical oceanography and water exchange in the Northern Kvark Strait. Continental Shelf Research, 26, 721-732. DOI 10.1016/j.csr.2006.01.012

- A: We thank Anders Omstedt (reviewer #1) for his time and effort. We agreed in our rebuttal that the paper would gain from an extended discussion about the ice dynamics in the test region. We added now such a discussion (line 66-82) and included additionally a respective Figure (Figure 2) into the revised manuscript. Also, the reference suggested by Anders Omstedt is now included into our reference list (line 70/455). Additionally, we introduced two new Figures to evaluate the sea ice model (Figure 3 and 4). In Figure 4 the simulated sea ice drift is compared to SAR-based ice drift estimates, as provided by Karvonen, 2012. Note, however, that according to Karvonen, 2012, the magnitude of the estimated ice drift is rather uncertain. Simulated ice concentration and thickness are, as expected due to the data assimilation, very close to the observations (Figure 3). We believe that the difficulties in finding reliable observation of other ice properties than concentration and thickness make the AIS data set particularly valuable for ice modelers.

Reviewer #2 (anonymous):

This is an interesting paper that uses AIS data to test whether or not there is a relationship between predictions of various sea ice properties from an ice forecasting model and ship speed. There is the potential for the results to have a large impact on how sea ice forecasts are used and interpreted by the shipping industry. In general, more detail and discussion is required to support the approach used by the authors.

- A: We thank reviewer #2 for his time end effort and helpful, encouraging comments.

1. How well does HIROMB perform in the study area? For example, are forecasts of convergence/divergence, drift speed and ridge density realistic?

- A: We added two Figures for model evaluation to the new manuscript (Fig.3 and 4). In Figure 4 the simulated sea ice drift is compared to SAR-based ice drift estimates, as provided by Karvonen, 2012. Still these estimates are rather uncertain and it is hard to find reliable observations of ice properties (other than ice concentration and thickness). We believe that this circumstance makes the AIS data set particularly valuable for sea ice modelers.

2. What is the rationale for determining which variables to include as fixed effects versus random effects? Ice drift, convergence and angle are only included as fixed effects, why?

- A: We aim to keep the number of estimated parameters as low as possible. Each additional factor included into the mixed effects would increase the degrees of freedom enormously and when including everything we would tend to overfit the data. We thus included the variables which showed the largest spread in ship speeds with decreasing median (according to the preceding data analysis; cf. line 274ff). This information was added to the revised manuscript (line 347ff).

3. In the discussion of Figure 3, I don't understand the references to non-linear relationships. Figure 3b looks similar to 2a-c?

- A: The non-linearity becomes more visible when using another partitioning of the velocity classes. In the first manuscript version, the class-width were, in contrast to the sub-plots in Figure 2, non-equal which we believe was confusing. We exchanged now the respective sub-panel (now Figure 6b).

4. I had a hard time following the discussion of Table 1 (page 3819). For example, where does it show that the strongest factor affecting ship speed is slow drift speeds with ice drift from the side of the ship? In general, I had a hard time linking most statements to the data shown in Table 1.

- A: Thanks. We will changed the description of the Table and refer explicitly to the respective numbers (cf. e.g. line 366, 369, 375ff, 390, 393ff).

5. The variables in Figure 2 are tested for correlation, why isn't this done for the mixed effect variables and is there an implication to the validity of the model if two of the random components (ridges and level ice thickness) are highly correlated?

- A: True. High correlations do not impact the validity of the statistical model and the predictive skill is not affected. However, the correlations are of interest since the impact of correlated variables can not be fully separated and the significance of one of the respective variables might be masked; i.e. we can not fully distinguish to what extent ice thickness compared to ridge density causes a median speed drop. We clarified this point in line 376ff. Also, we added the promised correlations (line 380ff).

Minor comments:

1. The model is developed using data from only one year, 2011, are there any caveats applying it to other years?

- A: There are no caveats we can think of. Our choice of 2011 for this pilot study was a pragmatic one (our momentary data access was limited).

2. In the discussion of Figure 2, I see the general decreases in the median and first quartiles but why are there general increases in the upper bound and extremes?

- A: We added now a discussion of this issue in line 276ff. We assume, that the ships aim to keep a relatively high speed whenever possible. When the ice conditions get severe, small ships will experience large speed drops while big ships with a strong engine are less affected. We expect, that this factor leads to an increased spread in ship speeds under sever ice conditions. This hypothesis is supported by the fact that the random intercepts are correlated with the random slopes (line 395ff).

3. Figure 3c represents a known situation where ships tend to get stuck. What about convergence and high ice concentrations? Are there other combinations of sea ice variables that lead to besetting in this region?

- A: Convergence in combination with high ice concentrations did not turn out to be a significant factor. This might well be related to

problems with the representation of convergences (cf. line 426ff)

Concerning ". . .other combinations. . .": We tested all interactions between explanatory variables but could not score any remarkable improvement of the statistical fit (according to the Akaike information criterion (AIC))). We added this information in line 343ff of the revised manuscript.

4. In general for Figures 2 and 3, how many observations are in each category? A difference in means test could be used to test the statistical significance of the difference in means between each category.

- A: After reconsidering, we have decided against listing all 28 numbers since we feel that this would complicate reading. Also we do test significance already when fitting the statistical model (cf. line 330, 344, 366 and table 1).

Page 3814 Line 8: typo "was developed in the 90th " Line 23: change to "regularly passed by ships" Line 24-25: awkward wording, maybe something like :::. "The region consists of relatively narrow passages with little space to circumnavigate problematic areas"

- A: Thanks (changed in now line 71)

Page 3815 Line 6: how many observations were excluded compared to the approx..14,000 included in the analysis

- A: The original table (without ice breakers) contained 16407 observations (we added this information in line140 in the revised manuscript).

Page 3818 Line 20:::. Change to "Fitting statistical models :::"

- A: Thanks (changed in line 327)

Page 3819 Line 1: How did you test the statistical significance? Was this significance test applied to all of the categories/variables in figure 2 and 3?

- A: We used a t-test when fitting the statistical model, while the preceding data analysis is purely heuristic. These information were added to the revised manuscript (line 326 and 331).

Manuscript prepared for J. Name
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Ice and AIS: Ship speed data and sea ice forecasts in the Baltic Sea

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Abstract. The Baltic Sea is a seasonally ice covered marginal sea located in a densely populated area in northern Europe. Severe sea ice conditions have the potential to hinder the intense ship traffic considerably. Thus, sea ice fore- and nowcasts are regularly provided by the national weather services. Typically, several ice properties are allocated, but their actual usefulness is difficult to measure and the ship captains must determine their relative importance and relevance for optimal ship speed and safety ad hoc.

The present study provides a more objective approach by comparing the ship speeds, obtained by the Automatic Identification System (AIS), with the respective forecasted ice conditions. We find that, despite an unavoidable random component, this information is useful to constrain and rate fore- and nowcasts. More precisely, 62-67% of ship speed variations can be explained by the forecasted ice properties when fitting a mixed effect model. This statistical fit is based on a test region in the Bothnian Bay during the severe winter 2011 and employs 15 to 25-min averages of ship speed.

1 Introduction

The Baltic Sea is a seasonally ice covered marginal sea located in a densely populated area in northern Europe with important shipping routes crossing the regularly ice covered regions. The ice season lasts up to 7 months (Vihma and Haapala, 2009). The maximum ice extent is typically reached in late February, showing large interannual variations between 12.5 and 100% (Leppäranta and Myrberg, 2009). In regions with long wind fetch the ice cover is often broken up and the ice is forced into motion (Uotila, 2001). Thus, the ice coverage here is not uniform but consists of ice floes of variable sizes, leads and deformed ice patches (Leppäranta and Myrberg, 2009). Ships have to find their way through this "drift ice landscape".

Since sea ice potentially hinders winter navigation, detailed forecasts of the ice conditions are in demand and regularly provided by the local weather services. A typical ice forecast contains several prognostic variables, for instance ice concentration, thickness and prognosticated ice drift. Additional variables are occasionally included, e.g., ridged ice fraction, which refers to the most important deformed ice type. Ridges can form substantial obstacles to the winter navigation and receive thus increasing attention form the research community (e.g., Haapala, 2000; Kankaanpää, 1988; Leppäranta and Hakala, 1992; Leppäranta et al., 1995; Löptien et al., 2013). The forecast of the Swedish Meteorological and Hydrological Institute (SMHI) provides additional information about convergence of the ice drift field (i.e., regions where the ice is compacting are marked). In regions with convergent ice motion, large ice stresses can occur, the ships might get stuck and, in the worse case, even damaged (e.g., Suominen and Kujala, 2013; Pärn et al., 2007).

Based on spatial maps of the sea ice properties above described, ship captains, supported by the **nationale maritime administrations**, must chose the supposably best route. It depends on the expertise of each captain on how to rate the relative importance of the forecasted variables in terms of ship speed and safety. Also, a typical forecast model has a horizontal resolution that ranges from 1-3nm (nautical miles; 1nm =1852m) and important processes acting on ship scale (i.e. a scale of a few hundred meters) might not be resolved.

The present study provides an objective assessment of how a typical ice forecast (provided by SMHI) compares to ship scale and how the various ice properties affect ship speed. **The study focuses on a test region in the Bothnian Bay (62.8°-63.6°N and 19.8°-21.0°E, Fig.1), which is regularly passed by ships and known for its severe ice conditions. The region is located south of the so called Kvark Strait (Green et al. (2006)), a narrow passage with lit-**

tle space to cirucmnavigate problematic areas. The mean ice drift in the test region is generally directed towards the northeast (Fig.2), but is the presence of high ice concentrations in the Bothnian Bay, the northward flow is limited (or even blocked). As, during March and April, the ice concentrations in the Bothnian Bay decrease, the transport through Kvark Strait accelerates. Still the narrowness of the passage leads to an accumulation of sea ice in the test region. This accumulation of sea ice makes it impossible for ships to fully avoid severe ice conditions and makes the region particularly interesting as test region. The corresponding ship speed observations are obtained by the Automatic Identification System (AIS). While the AIS-system comprises an unavoidable random component (e.g., ship captains might reduce speed due to reasons not related to sea ice), this large-scale comprehensive data set is available for research purposes without any extra costs. Due the large amount of ships which have a tight schedule and aim to keep a relatively constant high speed, we anticipate that the noise might well be on relatively low level and test the applicability of AIS-derived ship speeds for the evaluation of sea ice fore- and nowcasts. We explore to what extent observed ship speeds can be reconstructed based on the forecasted ice properties by fitting a mixed effect model. This statistical model resembles a multi-linear regression, but allows additionally for the inclusion of (construction-related) difference between individual ships.

A detailed description of the underlying data as well as the statistical method is given in the following Section. Section 3 shows the results of our data exploration and the statistical fit, followed by a conclusive summary in Sect. 4.

2 Methods

We compare ship speed observations to the corresponding (forecasted) ice properties. Both, ship speed observations and the ice forecast model, inclusive evaluation, are described in this Section (Section 2.1 and 2.2, resp.). After a preceding data exploration, we fit a statistical model. This, so called, mixed effect model is described in detail in Section 2.3.

2.1 Ship Speed Observations

The Automatic Identification System (AIS) was developed in the 90th and is an automatic tracking system for identifying and locating ships. The systems is based on an electronic exchange of data with other ships nearby, AIS-base station and satellites. The major aim is to avoid collisions by supplementing ship radars (Berking, 2003; Harati-Mokhtari et al., 2007). Additionally, it enables maritime authorities to monitor vessel movements. The "International Maritime Organization's International Convention for the Safety of Life at Sea" requires AIS to be installed aboard international voyaging ships with a tonnage of 300 tons and more, as well as on all passenger ships. AIS data contain inter alia an unique identification (MMSI number), position, course, and speed of a vessel. Since the data coverage increased considerably during the past two decades, the data set is increasingly used for scientific purposes (e.g., Montewka et al. (2010) assessed the collision risk of vessels; Jalkanen et al. (2009) and Miola et al. (2011) estimate the emissions of marine traffic).

The present analysis is based on a test data set, collected during the severe winter 2011 (January-April). We focus on a test region in the Bothnian Bay (62.8°-63.6°N and 19.8°-21.0°E, Fig.1) **with generally severe ice conditions and intense ship traffic. No harbours are included in this test area**. Ship speed and direction are calculated from the ship locations every 5 minutes. All observations $\pm$1h around an ice forecast (which is provided 4x daily) are analyzed. Ships close to ice breakers (within a rectangle of 0.2nm (= 370.4m)) as well as ice breakers themselves are excluded from the analysis (as they add an unforeseeable random component). **The resulting data table comprises of 16 407 entries.** Since we could not detect any systematic drop of ship speeds at ice concentrations below 60% those data are not considered. We exclude also all ships that remained only 25 min or less in the test region (since mixed effect model requires a sufficient amount of available data per ship).

Ultimately, the analyzed data set consists of observations from 319 different ships, with an average duration of stay of 215 minutes in the test region. Overall $\sim$14 000 observations were included into the statistical analysis.

2.2 Ice Forecast Model

The ice forecasts are based on the operational coupled ocean-ice forecast model HIROMB (High Resolution Operational Model for the Baltic) of SMHI. It includes a three-dimensional, baroclinic ocean model, covering the Baltic Sea and North Sea (Funkvist and Kleine, 2007). The ocean model is coupled to a Hibler-type sea ice model (as described by Wilhelmsson (2002); extensions by Kotovirta et al. (2009) and Axel (2013)). The horizontal resolution ranges from 3nm (nautical miles; 3nm= 5556m) in the North Sea to 1nm (=1852m) in the Skagerrak-Kattegat area.

The forecasts includes data assimilation of salinity, temperature and various ice properties. These latter are provided by the operational ice service at SMHI and comprise ice concentration, level ice thickness, and "degree of ridging" (which is used to approximate ridge density, following the approach of Lensu (2003)). The data are based on in situ measurements, estimates from voluntary ships and ice breakers as well as satellite observations. The degree of ridging is a number describing how heavily ridged a region is (as perceived by the ice analyst). Based on the approach of Lensu (2003) this number is tentatively converted to the more common measure "ridge density" (= number of ridges per km). Note, this number is approximate only.

Apart, from the assimilated ice properties described above, the model output covers ice drift in *u* and *v* direction as well as divergence of the ice motion. Divergence is defined as the sum of the derivatives of the ice flow field in *u* and *v* direction. As such negative values stand for areas where the ice is compacting (i.e., convergent ice motion). Auxiliary classifications of the ice thickness are available but not included into the following analyses. since they do not provide new independent information.

To evaluate the sea ice model, independently form the AIS-data, ideally large scale observations, which are not already included into the data assimilation, are needed. Ice thickness and concentration are available as digitized ice charts, which are provided daily by the Finnish Meteorological Institute (FMI). The charts summarise the available ice information for shipping, based on manual interpretation of satellite data and ground truth. The underlying observations are provided, e.g., by icebreakers, voluntary observing ships, ports and station observation stations of the Baltic ice services and are in large parts independent form the swedish observations (which are assimilated into HIROMB). The generally close match of observed and simulated ice thickness and concentration (Fig.3) is not surprising, given the assimilation of this relatively well observed variables. It is, however, difficult to find reliable observations of other ice properties. One recent attempt estimates ice drift based on Synthetic Aperture Radar (SAR)-images (Karvonen (2012)). The data are provided within the MyOcean Project. Despite the known uncertainties and sparseness of the provided data, the data set is still unique regarding its spatial coverage. According to Karvonen (2012), the ice drift direction is relatively well estimated while the magnitude might often be biased. The data set consists of ice displacement (in m), estimated from two successive SAR images over the same area. Two exemplary snapshots of the derived velocities at times with a relatively high data coverage are shown in Figure 4. As ice drift is not directly assimilated and given the uncertainty in the observations, it seems reasonable that the agreement between modelled and observed ice drift is not as close as for thickness and concentration. Particularly, the simulated sea ice is more mobile than implied by the SAR estimates, while the ice drift direction and the major patterns agree rather well. An overestimation of ice drift speed in coastal regions was expected, as land-fast ice is not considered extra by the model. Nevertheless, one should bear in mind, that even though ice drift is not directly assimilated this occurs to a certain degree indirectly, as it can not evolve completely free due to the constrains given by assimilating ice thickness and concentration. Unfortunately, the SAR-estimates seem to patchy for reliable estimates of divergence.

2.3 Statistical Analysis

After some preceding data exploration, we aim to test how well we can reconstruct the ship speed observations by the forecasted ice properties. For this purpose, we fit a mixed effect model. A mixed effect model is an extension of a common multi-linear regression (e.g., Zuur et al., 2007), which accounts for the differences between individual ships (depending on ice class, shape and size of a vessel, engine power etc.). A multi-linear regression alone would not be able to capture these often substantial differences. In matrix notation a mixed effect model can be written as:

$$y_i = X_i\beta + Z_iu_i + \epsilon_i. \quad (1)$$

Here, i=1,..,N indexes the MMSI numbers and y_i denotes a vector of observations per ship (=dependent variable) which consists here of the square root of the speed of individual vessels during consecutive 5-minute time steps. The square root is taken to bring the data closer to normality.

The vector β stands for the "fixed effects" and has the same value for all ships. u is a vector of so called "random effects" (with mean 0), which entries are allowed to vary between individual ships (which are uniquely identified by the MMSI-numbers).

X and Z denote matrices of regressors, relating the observations to β and u. When omitting the term Zu_i, the formula corresponds to a common multi-linear regression. Since generally not every single ship-dependent regression parameter in u is of interest, but rather the overall properties (e.g. variations and covariability), u is termed "random". The matrices X and Z may, or may not, contain the same explanatory variables. In the present study we chose X to contain ice concentration, level ice thickness, ridge density, ice drift speed, convergence and the angle in which the ship is moving relative to the ice movement (factorized as in **Fig.6c**). **To keep the number of estimated parameters as low as possible and to avoid overfitting, we include only those variables into Z which showed, in a preceding data exploration, indications for large variations among the ships (cf. Section 3.2) and merely ice concentration, level ice thickness and ridge density were considered here**. Additionally we allow for a ship dependent intercept (i.e., points were the regression lines cross the y-axis), accounting for the different mean speeds of individual vessels. As usual, ϵ_i represent a random noise component ($\epsilon_i \sim N(0, \sum_i)$, iid).

3 Results

3.1 Data Exploration

First, we explore the distribution of ship speeds for different ice concentrations, ice thicknesses and ridge densities (**Fig.5**). To visualise the large amount of data, the ice properties are binned into several classes and subsequently the ship speed distributions are analyzed per ice property class. This analysis shows that the median ship speed per bin, as well as the upper quantiles, decreases strongly with increasing ice concentration (**Fig.5a**). While the median speed is around 14kn (knots; 14kn=7.2m/s) for ice concentrations between 60-65%, this value decreases to 4-5kn (≈2-2.6m/s) at ice concentrations between 95-100%. For level ice thicknesses below 30cm, a similar decrease of the median ship speed occurs with increasing ice thickness. Interestingly, no further systematic speed drop occurs for thicknesses above 30cm (**Fig.5b**). **Also, it is interesting to note that the variability in observed ship speeds increases with both, increasing ice concentration and thickness. We anticipate that the increased spread of ship speeds with decreasing median reflects the varying abilities of differing vessels to cope with the ice conditions. As ice concentration and thickness increase, small ships will in general experience very large speed drops while big ships with strong engines are less affected. We conclude that all variables with a pronounced increase in the spread of ship speeds with decreasing median might strongly benefit from a random component when fitting the mixed effect model. Such a link exists, beside for ice concentration and thickness, also for the amount of ridged ice. Fig.5c** shows a considerable decrease in median ship speed **in combination with an increase in the variability** as ridge density exceeds a value of 1 ridge/km (from ≈13kn to ≈8kn or ≈6.7m/s to ≈4m/s) but no clear drop as ridge density increases further. Note, that the latter result might partly be due to the uncertainties in the precise values of the assimilated ridge densities.

Figure 6 shows a similar analysis as **Figure 5** but focuses on strong non-linear and factorized relationships. Note, that in contrast to the prognostic variables analyzed in **Figure 5**, these factors are based on prognostic variables which are not assimilated into HIROMB. The first investigated factor covers convergence in the ice drift field. As in the released forecast product, we distinguish convergent from nonconvergent ice motion and do not consider the magnitude. **Figure 6a** illustrates that the ship speed distributions are surprisingly similar under convergent and non-convergent ice motion. In contrast, simulated ice drift speed occurs to be influential while the impact is non-linear (Fig.6b). Particularly, very slow moving, almost stationary ice is related to a considerable median speed drop but also fast moving ice seems to affect the ship traffic. **To factorise this non-linear relationship for the following statistical fit (Section 3.2), we distinguish four (non-equidistant) ice velocity classes: stationary ice (0-0.04m/s), slow moving ice (0.04-0.1m/s), medium speed (0.1-0.3m/s) and fast moving ice (>0.3m/s). Another** particular problematic situation for ships is illustrated in Figure 6c. Very slow moving ice in combination with a drift angle close to 90° relative to the ship movement is related to a reduction in median ship speed to values close to zero (Fig.6c). This finding is inline with experiences from naval architects (pers. communication Kaj Riska, ILS, 2012), who report that ship routes with ice drift from the side of the ship result generally in a closing of the ship channels and might cause considerable ice pressure on the ship hull on a large contact surface. At the same time, high ice pressure is generally related to high ice concentrations and accordingly slow ice drift.

3.2 Mixed Effect Modelling

After the purely heuristic data exploration, fitting a statistical **model** allows us to **investigate** the relation between the various ice properties and ship speeds systematically. The aim is to test how well we can reconstruct the ship speed observations by the forecasted ice properties. **The statistical significance is tested by using a t-test**. A good agreement between this ship speed reconstruction and observed ship speed implies that the noise level in the ship speed observations is sufficiently small to use the data for model evaluation. At the same time it illustrates the actual usefulness of the ice forecast to estimate delays in the time schedule of ships. **As described above, we fit a mixed effect model based on ice concentration, level ice thickness, ridge density, ice drift speed and the factor according to Figure 6c (cf. Section 2.3). Divergence was excluded from the final statistical model, since the impact of simulated convergent ice motion appeared, in agreement with the foregoing data analysis, not to be statistically significant at the 5%-level. Similarly, all interactions among the above variables could not score any remarkable improvement of the statistical fit (according to the Akaike information criterion (AIC)) and were not considered. Random intercept and slope are included for ice thickness, ice concentration and ridge density, as the preceding data exploration of these variables revealed a pronounced increase in the variability of ship speeds with decreasing median.**

The reconstruction of ship speed based on the mixed effect model yields a remarkably close relation with the original observations: the correlation between square root of observed ship speed and reconstruction is 0.7, which implies that ≈50% of the variance in ship speed can be explained by the modeled ice properties. When smoothing the data with a running mean of 15 min, this correlation increases considerably to 0.79. For a running mean over 25 min we obtain a correlation of 0.82, which refers to an explained variance of 67%. Typical examples for the corresponding multilinear regressions for individual ships are shown in **Figure 7**. In agreement with the foregoing data exploration, the impacts of ice concentration, level ice thickness and ridge density appear to be highly significant **(as the p-values in Table 1 are clearly below 0.05)**. The forecasted ice concentrations seem to have the largest impact **among the contineous variables, as the estimated mean slope has the largest amplitude among the normalized continuous variables (-1.01, cf. column1, Table 1)**. Ice drift speed appears as well significant, while the relation is, in agreement with the foregoing data exploration, non-linear. The strongest factor affecting ship speed, are the relatively rare situations were the ice drift is very slow and the ice drift is directed from the side of the ship **(according to Table 1 the estimated impact of this factor is -0.63)**. **Note, that the effects of ridges and level ice thickness can not be fully separated, since both quantities appear to be correlated with 0.53. This relatively high correlation is reasonable since thin level ice will raft rather than form ridges when deformed. Additional weakly negative correlations occur between ice drift speed and ice thickness (-0.3) as well as with ice concentration (-0.14). These correlations do not impact the validity or forecast suitability of the statistical model, but rather complicate the interpretation of the impact of the respective variables. Namely, the impact of two highly correlated variables can not be distinguished.**

Table 2 provides information about the random components. **The standard deviations are listed in column 1 and amounts to 1.02 for the the residuals**. The random intercept has a standard deviation of 1.71, while the standard deviation ranges from 1.37 to 2.22 for the random slopes. **The remaining columns in Table 2 refer to the correlations among the random slopes (column 3-4) and the correlations of the random slopes to the random intercept (column 2). The correlation between the random intercept and the random slope related to ice concentration is -0.79**, indicating that faster ships are generally less impacted by high ice concentrations. The same holds for ice thickness and ridge density - but here the relation is somewhat weaker (correlations to the random intercepts are -0.57 and -0.43, respectively).

4 Conclusions

Our analysis illustrate that, for a test data set, a large part of observed ship speed variations can well be reconstructed by the corresponding forecasted ice properties (Fig.7) and on average 62-67% of the ship speed variations can be explained (when considering 15-25 min averages). These large explained variances have two major implications. First, the ship speed observations obtained form the AIS-system appear to be useful to evaluate sea ice fore- and nowcasts - despite some unavoidable random component inherent to this data set. This finding might be of large interest, in particular as ship traffic in the Arctic and with that the demand for sea ice forecasts increases. **Specifically, the need for forecasted ice properties exceeds information on ice concentration and thickness which are difficult to evaluate otherwise.** Note, however, that we regard our study as a pioneer study and the stability of the results for other regions, ship types etc. remains to be tested in studies to come.

The second implication of the close fit, is a proven usefulness of the respective ice forecast for shipping. Despite the fact that the regression parameters vary strongly form ship to ship (Tables 1 and 2), this is remarkable since the impact of non-resolved small scale processes was not entirely clear. The impact of all provided prognostic variables, apart from convergence, appears to be significant. The surprisingly weak relation between ship speed and convergent ice drift might be related to shortcomings in the modeled ice drift, which amplify when deriving convergence. A well known problem in this context, yet be solved, is the often poor simulation of the ice drift related to the land fast-ice zone. As illustrated in Löptien and Dietze (2014) (their Fig.6), our test region might well be affected by this problem.

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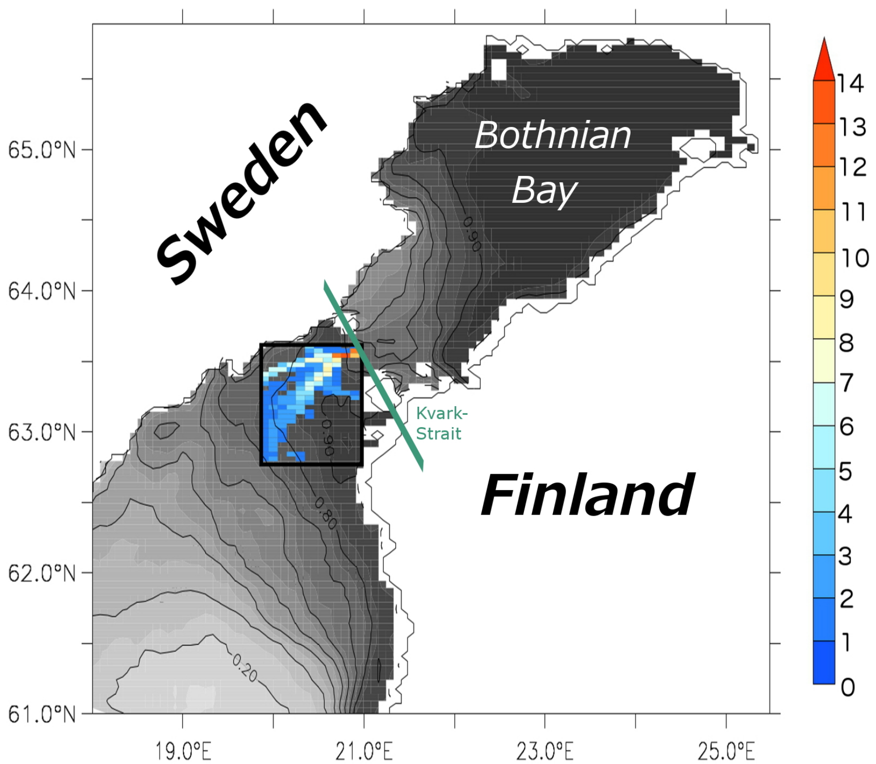

Fig. 1. The test region considered in this study is depicted by the black box. Blue shading refers to the average number of ships per day and 3x3nm (=5556x5556m) grid box in winter 2011 (January-April). Gray shading and contour lines depict the average ice concentrations during that winter (SMHI forecast). Contour intervals are 0.1.

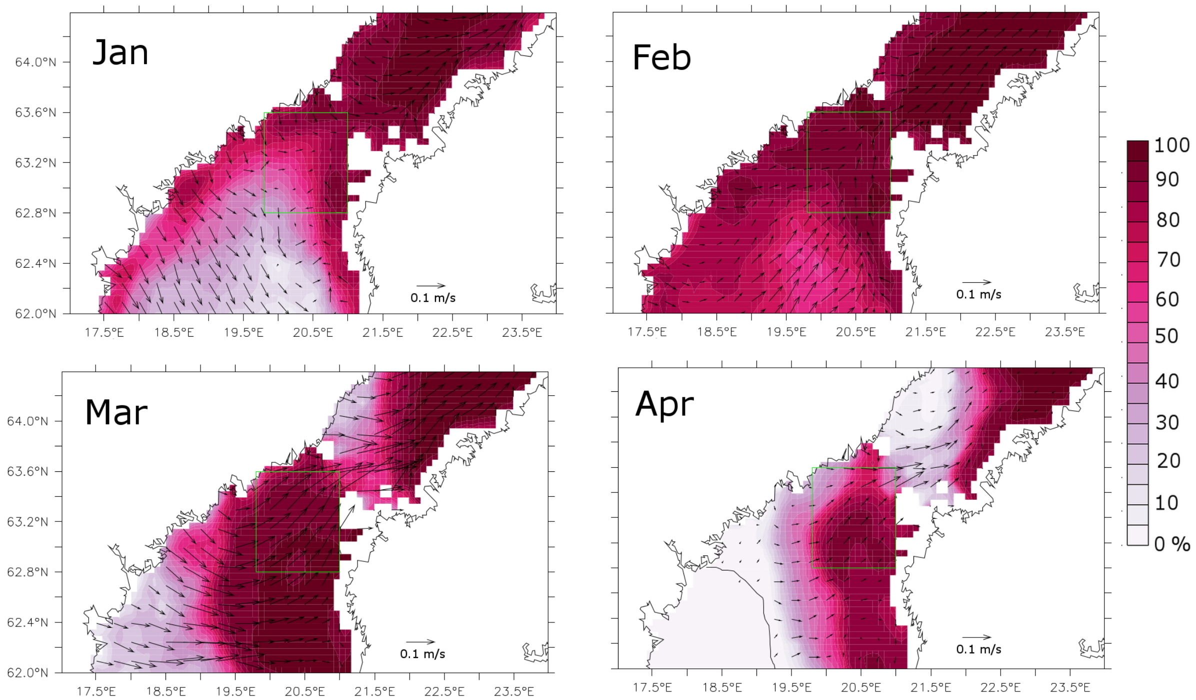

Fig. 2. (a-d) Forecasted monthly mean ice concentration and ice drift in winter 2011. The squares mark the test region considered in this study.

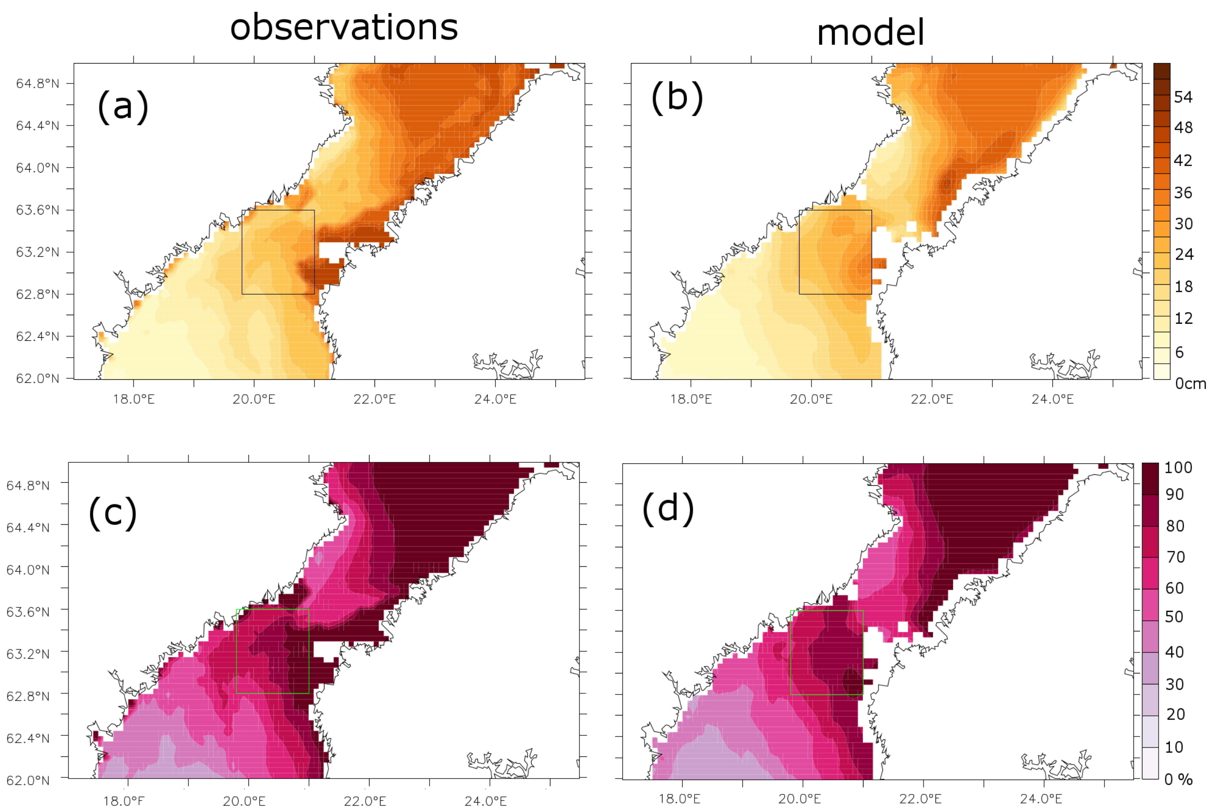

Fig. 3. Mean forecasted and observed (a, b) ice thickness and (c, d) ice concentrations during winter 2011 (JFMA). The squares mark the test region considered in this study. Fig (a) and (c) were generated by using MyOcean Products.

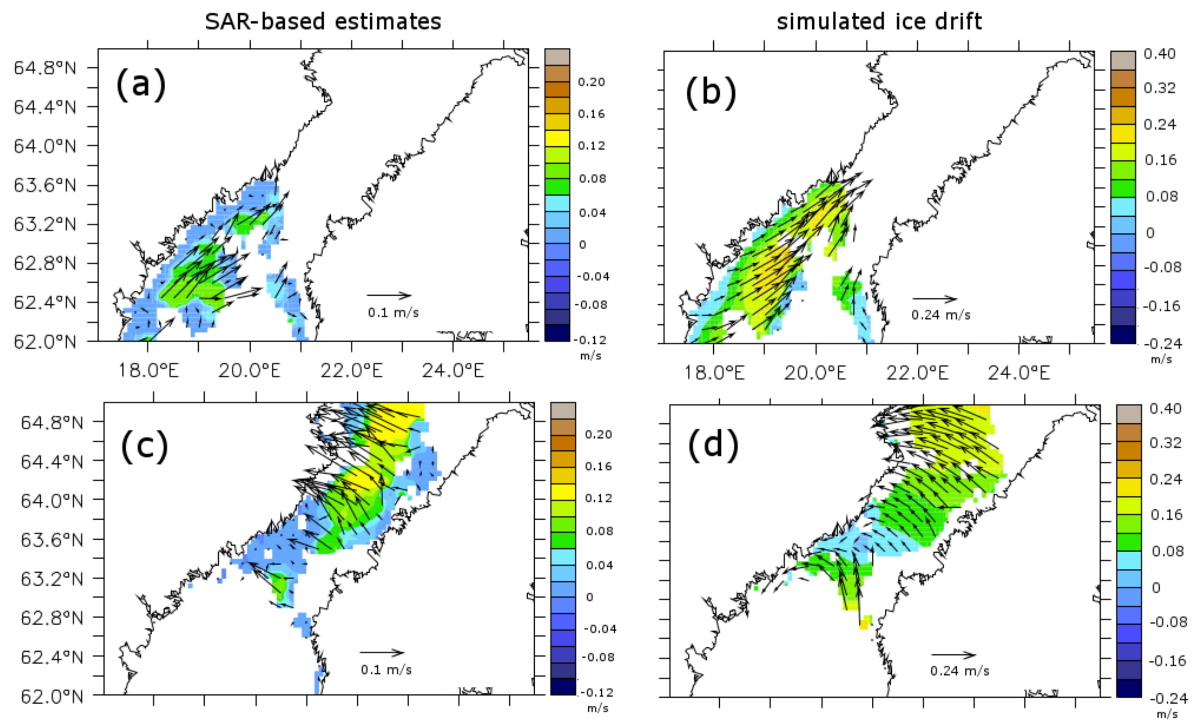

Fig. 4. (a,c) Two exemplary SAR-based ice drift estimates compared to (b,d) the forecasted ice drift. The arrows depict ice drift and the colours indicate the respective vector lengths. Fig.(a) refers to the SAR-based estimates of sea ice displacement during the time period between the 20st January, 20:17 and the 21rst January, 16:12, interpolated on the model grid. Fig.(b) depicts an average of all 6-hourly forecast model outputs included into this period. Likewise, Fig.(c) refers to the SAR-baed estimate during the time period between 1st February, 15:51 and the 3rd February, 05:03. Fig.(d) refers to the corresponding average of 6-hourly model snapshots. Observe the different arrow length in Fig (a) and (b) (resp., (c) and (d)). Fig (a) and (c) were generated by using MyOcean Products.

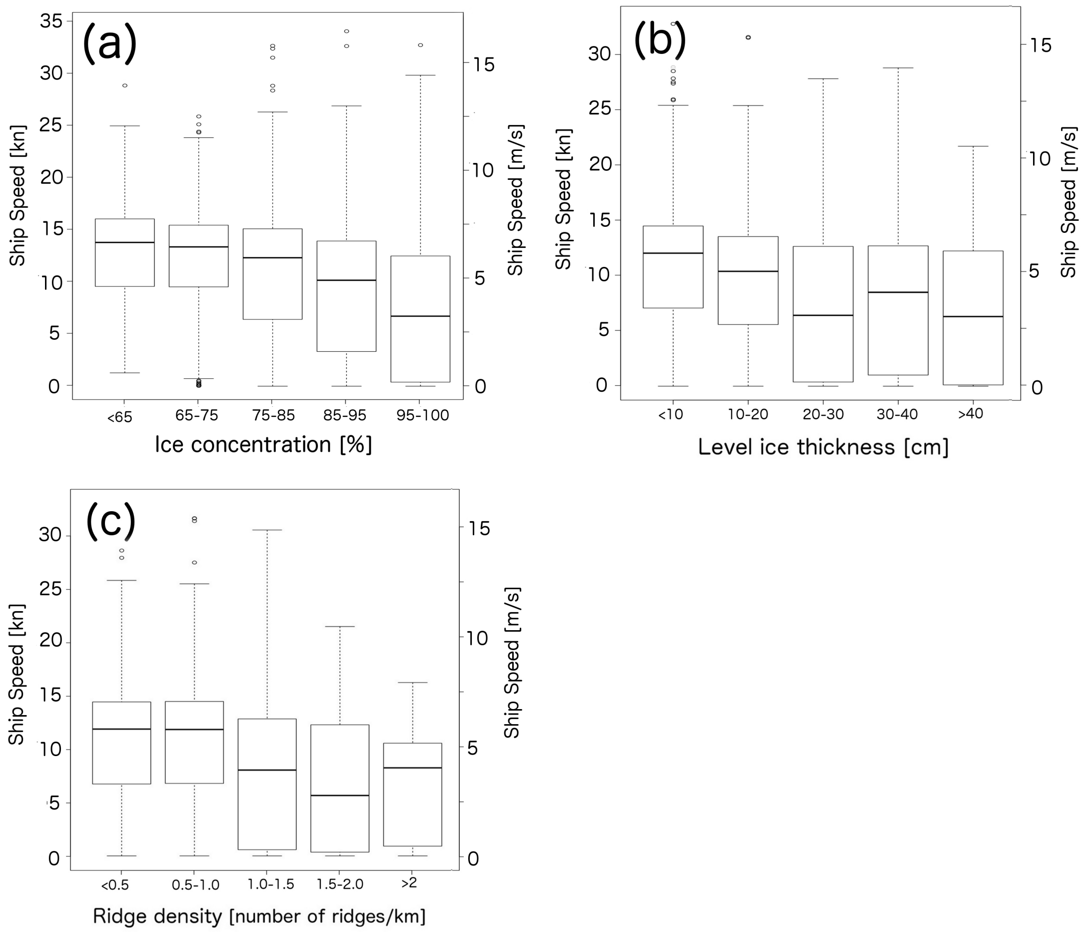

Fig. 5. (a-c) Observed ship speed distribution under several (binned) ice conditions, described by box plots. The bottom and top of the boxes are the first and third quartiles while the thicker band inside the boxes depicts the median. Lines extending vertically from the boxes (whiskers) depict ship speeds within 1.5 times the interquartile range from the box. Outliers are plotted as individual points. Panel (a) refers to ice concentration, (b) ice thickness and (c) ridge density.

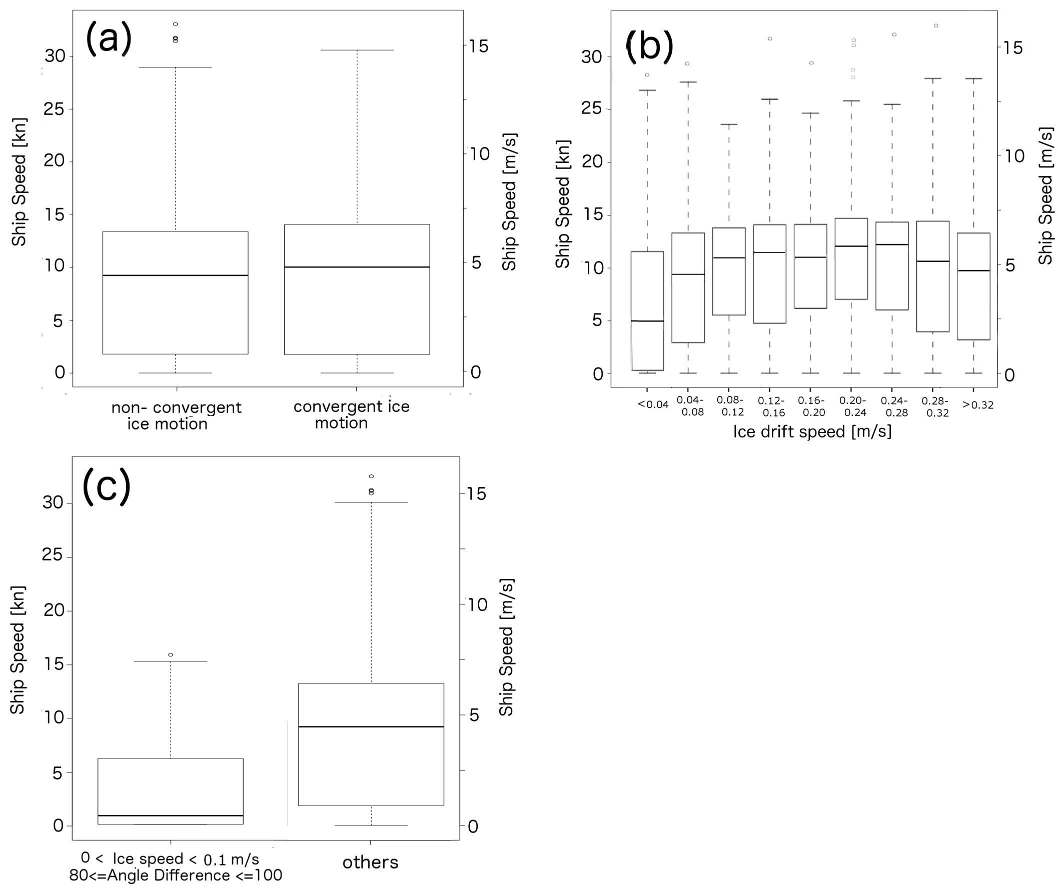

Fig. 6. (a-c) The distribution of observed ship speeds under various ice related factors. As in Figure 5 the respective distribution of ship speeds is depicted by box plots. Panel (a) refers to convergent and non-convergent ice motion, panel **(b) explores various classes of ice drift speed** and panel (c) refers to the specific situation where the ice is drifting very slow (<0.1m/s) and additionally the ice drift angle is close to 90° relative to the ship course. (Naturally, only data sets with ship and ice speeds >0 could be considered.)

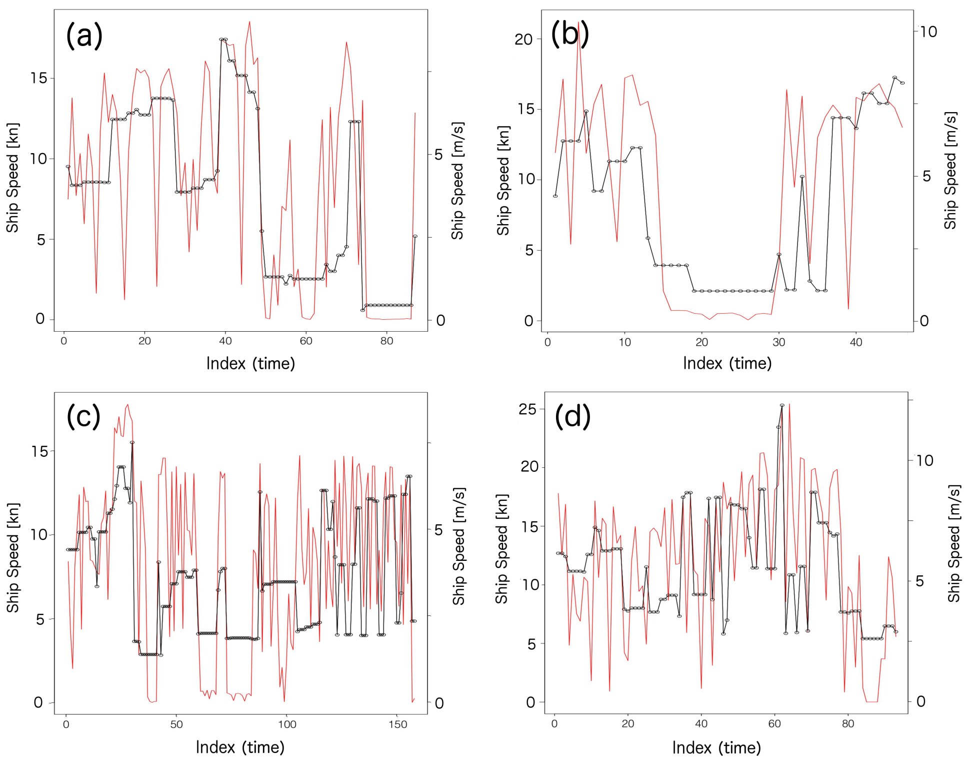

Fig. 7. (a-d) Observed (red lines) and reconstructed (black line) ship speeds for typical vessels in the test region: (a) General Cargo, 120m (b) Oil Tanker, 140m, (c) Cargo, 117m, (d) RoRo, 166m. The reconstructions are based on a multi-linear regression of forecasted ice concentration, level ice thickness, ridge density, ice speed and an additional factor which is based inter alia on the angle in which the ship is moving relative to the ice movement (parameterized as described in Fig.3c).

Table 1. Summary of the parameters obtained by fitting the mixed effect model.

	Value	**Std.Error**	p-value
Intercept	3.96	0.13	0.0000
Normalized Ice Concentration	-1.01	0.12	0.0000
Normalized Ice Thickness	-0.85	0.17	0.0000
Normalized Ridge Density	-0.63	0.12	0.0000
Factor:Ice Speed 0.04-0.10m/s	0.38	0.03	0.0000
Factor:Ice Speed 0.10-0.30m/s	0.45	0.03	0.0000
Factor:Ice Speed >0.30m/s	0.12	0.04	0.0028
Factor:Ice Speed <0.40m/s & Angle $\sim 90^\circ$	-0.63	0.12	0.0000

Table 2. Random components of the mixed effect model.

	Stdev.	**Corr. Intercept**	**Corr. Conc.**	**Corr. Thick.**
Intercept	1.72			
Normalized Ice Concentration	1.62	-0.79		
Normalized Ice Thickness	2.22	-0.57	0.10	
Normalized Ridge Density	1.37	-0.45	0.31	-0.04
Residual	1.02			