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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 employes 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 administrative office for seafaring affairs vessel traffic services, 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 1–3 nm (nautical miles; 1 nm = 1852 m) 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. 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.

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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

2.1 Ship 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), which is regularly passed and ships and known for its severe ice conditions. The region consists of a relatively narrow passage that does generally not allow to cirucmnavigate problematic areas. No harbours are included in this test area. Ship speed and direction are calculated from the ship locations every 5 min. All observations ±1 h around an ice forecast (which is provided 4× daily) are analyzed. Ships close to ice breakers (within a rectangle of 0.2 nm (= 370.4 m)) as well as ice breakers themselves are excluded from the analysis (as they add an unforeseeable random component). 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 min in the test region. Overall ~ 14 000 observations were included into the statistical analysis.

2.2 The 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 Axell, 2013). The horizontal resolution ranges from 3 nm (nautical miles; 3 nm = 5556 m) in the North Sea to 1 nm (= 1852 m) 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.

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 (e.g., Zuur et al., 2007). A mixed effect model is an extension of a common multi-linear regression , 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:

$$\boldsymbol{y}_i = \mathbf{X}_i\boldsymbol{\beta} + \mathbf{Z}_i\boldsymbol{u}_i + \boldsymbol{\epsilon}_i. \quad (1)$$

Here, $i = 1,...,N$ indexes the MMSI numbers and $\boldsymbol{y}_i$ 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 min time steps. The square root is taken to bring the data closer to normality.

The vector $\boldsymbol{\beta}$ stands for the "fixed effects" and has the same value for all ships. $\boldsymbol{u}$ 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).

$\mathbf{X}$ and $\mathbf{Z}$ denote matrices of regressors, relating the observations to $\boldsymbol{\beta}$ and $\boldsymbol{u}$. When omitting the term $\mathbf{Z}\boldsymbol{u}_i$, the formula corresponds to a common multi-linear regression. Since generally not every single ship-dependent regression parameter in $\boldsymbol{u}$ is of interest, but rather the overall properties (e.g. variations and covariability), $\boldsymbol{u}$ 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. 3c), while we include only ice concentration, level ice thickness and ridge density into **Z**. 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, $\boldsymbol{\epsilon}_i$ represent a random noise component ($\boldsymbol{\epsilon}_i \sim N(0, \sum_i)$, 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. 2). 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. 2a). While the median speed is around 14 kn (knots; $14\,\mathrm{kn} = 7.2\,\mathrm{m\,s^{-1}}$) for ice concentrations between 60–65 %, this value decreases to 4–5 kn (≈ 2–$2.6\,\mathrm{m\,s^{-1}}$) at ice concentrations between 95–100 %. For level ice thicknesses below 30 cm, a similar decrease of the median ship speed occurs with increasing ice thickness. Interestingly, no further systematic speed drop occurs for thicknesses above 30 cm (Fig. 2b). Another ice property, which is suspected to affect ship speed strongly, is the degree of ridging. Figure 2c shows a considerable decrease in median ship speed as ridge density exceeds a value of 1 ridge $\mathrm{km^{-1}}$ (from ≈ 13 kn to ≈ 8 kn or $\approx 6.7\,\mathrm{m\,s^{-1}}$ to $\approx 4\,\mathrm{m\,s^{-1}}$) but no clear drop as ridge density increases further. Note, that this result might partly be due to the uncertainties in the precise values of the assimilated ridge densities.

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Figure 3 shows a similar analysis as Fig. 2 but focuses on strong non-linear and factorized relationships. Note, that in contrast to the prognostic variables analyzed in Fig. 2, 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 non-convergent ice motion and do not consider the magnitude. Figure 3a 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. 3b). 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. A particular problematic situation for ships is illustrated in Fig. 3c. 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. 3c). 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

Fitting a statistical models allows us to explore 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. 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 with random intercept and slope for ice thickness, ice concentration and ridge density. As the impact of simulated convergent ice motion appeared, in agreement with

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the foregoing data analysis, not to be statistically significant at the 5 %-level, it was excluded from the final statistical model.

The reconstruction of ship speed based on the mixed effect model reveals 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 multi-linear regressions for individual ships are shown in Fig. 4. In agreement with the foregoing data exploration, the impacts of ice concentration, level ice thickness and ridge density appear to be highly significant. The forecasted ice concentrations seem to have the largest impact (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.

Table 2 provides information about the random components. The standard deviation of the residuals is 1.02. 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 random intercept is correlated with the random slope for ice concentration by a factor of −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). 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 (while ice concentrations are hardly correlated with both ice thickness (−0.06) and ridge density (0.02)). This relatively high correlation is reasonable since thin level ice will raft rather than form ridges when deformed.

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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. 4) 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. 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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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 40–100 cm s^{-1}	0.38	0.03	0.0000
Factor:Ice Speed 100–300 cm s^{-1}	0.45	0.03	0.0000
Factor:Ice Speed $> 300\,\text{cm s}^{-1}$	0.12	0.04	0.0028
Factor:Ice Speed $< 40\,\text{cm s}^{-1}$ and Angle $\sim 90°$	−0.63	0.12	0.0000

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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			

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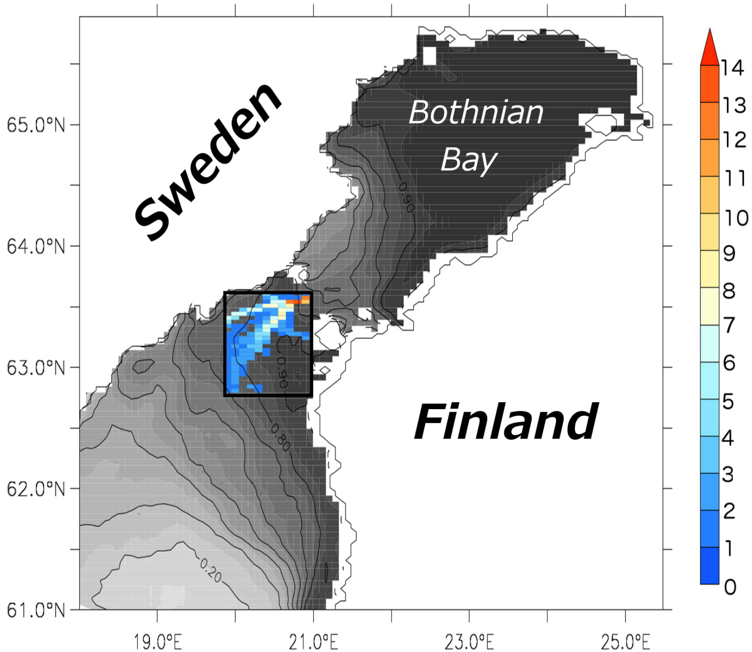

Figure 1. The test region considered in this study is depicted by the black box. Blue shading refers to the average number of ships per day and 3 nm × 3 nm (= 5556 m × 5556 m) grid box in winter 2011 (January–April). Gray shading and contour lines depict the average ice concentrations during that winter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

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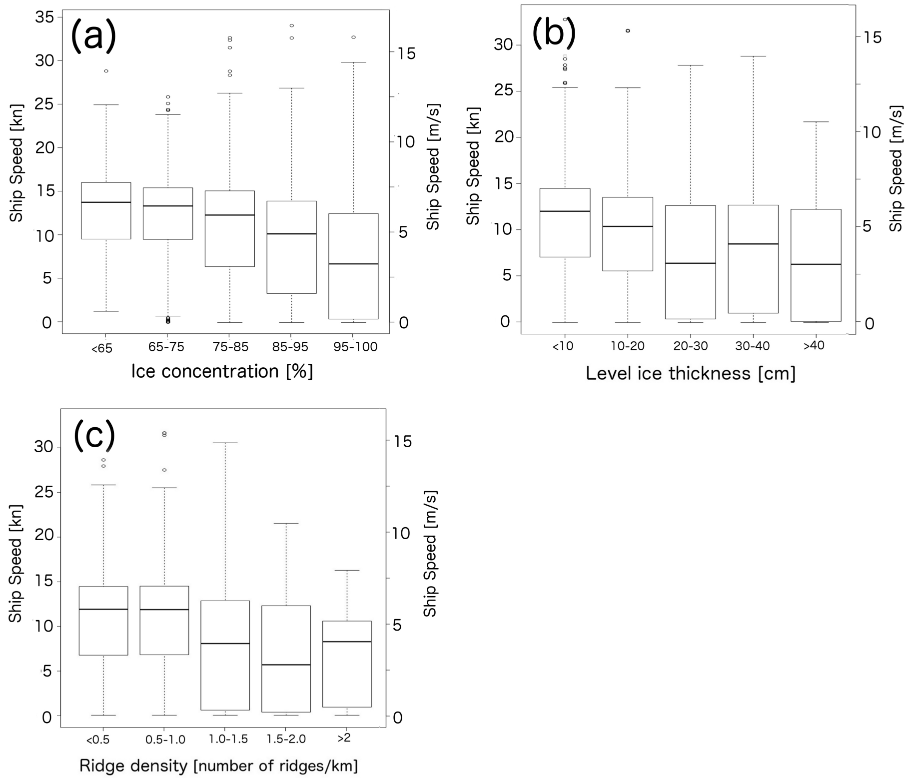

Figure 2. (a–c) Observed ship speed distribution under several (binned) ice conditions, described by box plots. The bottom and top of the boxes are the first and third quartiles while the thicker band inside the boxes depicts the median. Lines extending vertically from the boxes (whiskers) depict ship 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.

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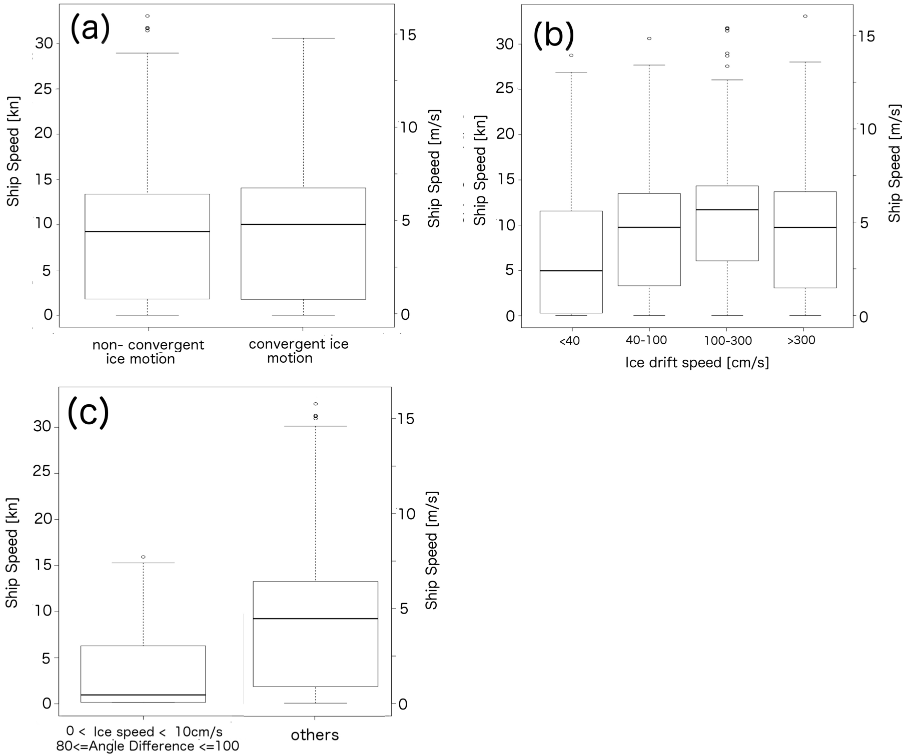

Figure 3. (a–c) The distribution of observed ship speeds under various ice related factors. As in Fig. 2 the respective distribution of ship speeds is depicted by box plots. Panel **(a)** refers to convergent and non-convergent ice motion, panel **(b)** explores various classes of ice drift speed and panel **(c)** refers to the specific situation where the ice is drifting very slow ($< 10\,\mathrm{cm\,s^{-1}}$) 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.)

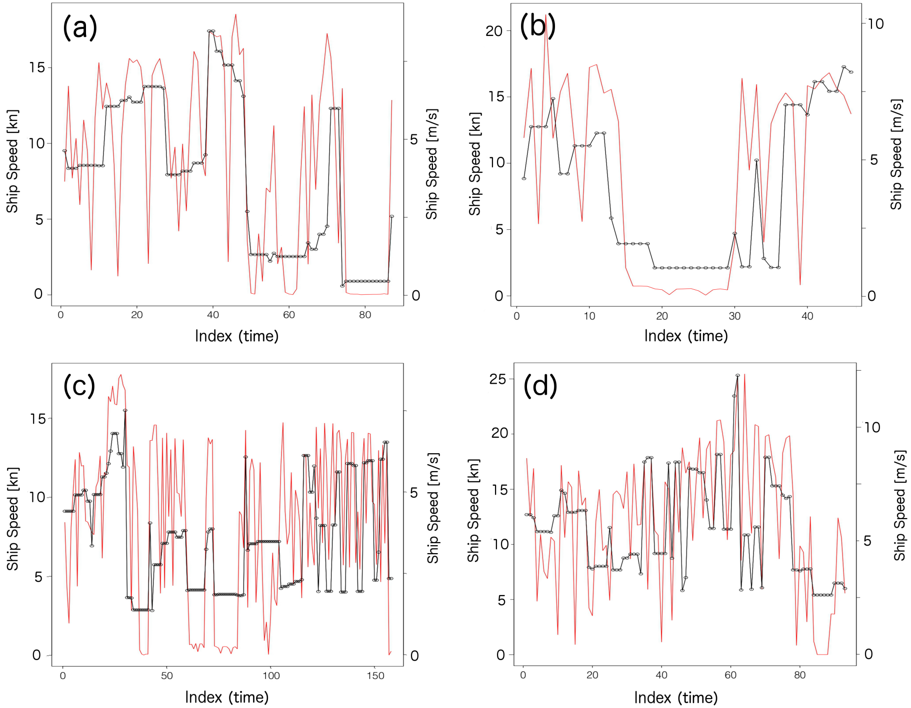

Figure 4. (a–d) Observed (red lines) and reconstructed (black line) ship speeds for typical vessels in the test region: **(a)** General Cargo, 120 m **(b)** Oil Tanker, 140 m, **(c)** Cargo, 117 m, **(d)** RoRo, 166 m. The reconstructions are based on a multi-linear regression of forecasted ice concentration, 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).