POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, UK

Caspian Ice Cover Mobility

Anton Sigitov[1], Yevgeniy Kadranov[1], Sergey Vernyayev[1], Irina Vernyayeva[1]
[1] ICEMAN.KZ LLP (Almaty, Kazakhstan)

ABSTRACT

Ice cover mobility is one of the most important ice cover parameters that allows estimating possibility of ice events and mode of ice interaction with offshore structures. It allows aggregating possible parameters when compiling scenarios for assessment of hazardous conditions affecting marine operations and emergency escape. This paper provides insights into temporal and spatial distribution of ice cover mobility over the Northern part of the Caspian Sea from 2005 to 2023 and its application for engineering purposes.

KEY WORDS Caspian Sea; Ice database; Ice charting; Regional ice monitoring; Ice mobility.

NOMENCLATURE (Optional)
AARI (Arctic and Antarctic Research Institute), FDD (Freezing Degree Days), SAR (Synthetic Aperture Radar), WMO (World Meteorological Organization)

INTRODUCTION

Either landfast or drifting ice normally dominates over study areas in the Arctic region. Whereas peculiarity of sub-Arctic seas is limited ice thickness and regular change between cold snaps and thaw periods. Kaartokallio et al. (2016) discusses these and more peculiarities of ice cover development in the subarctic seas in more detail. Monitoring ice cover mobility becomes important to ensure sufficient knowledge on effect of wind events that destabilize previously fast areas. Most importantly statistics based on observations facilitates quantified ice hazards analysis and forecasting potential impact to operations.

Nevertheless, WMO (2004) guidelines and WMO (2014) data structure for ice charting data do not regulate collection of this parameter. Thus, standard data acquisition and monitoring programs designed based on these documents do not record the state of ice cover. Scarce publicly available information on ice cover characterization collected by AARI, KazHydroMet and a few other agencies confirm the reliance on these standards that one of the most important parameters is missing from the databases.

Operational experience by ICEMAN.KZ that was introduced into design of ice cover classification database in the initial stages of Caspian ice cover classification hindcast program as described by Vernyayev et al. (2023a) has defined the parameter as an absolute necessity to deliver quality analysis and forecasts based on the collected data. Daily ice cover mobility was, thus, collected alongside with standard parameters like ice concentration, thickness (stage of development), dominating floe sizes that were assigned to areas of homogeneous ice conditions present.

Throughout analytical products, ice mobility or immobility with clear definition, regular and consistent observations became an important events descriptor supporting detailed scenario-based assessment of ice impact on operations. Applications vary from operational forecasts where the history of destabilization due to wind events as described by Vernyayev et al. (2023c) to long term outlooks on evolution of ice cover under changing climate conditions affects the frequency of operations with deployed structures in the region. Ice cover mobility is also important to assess operational conditions of units deployed for support and emergency evacuation purposes in ultra-shallow waters of the region. Custom case comprising cross-drift in channels as described by Bukharitsin et al., 2019 has been improved with introduction of classification of ice cover mobility removing uncertainties in the analysis while using other observations. As performance of deployed or custom designed units are sensitive to variation of ice thickness, frequency of extreme ice features like ridged areas and ridges additional factor of moving ice cover makes it a substantial change for their normal expected operation.

This paper demonstrates the data collection program and some examples of practical applications where the dataset was used.

ICE MOBILITY DEFINITION

Operational experience has guided the following definition and associated practical meaning of introduced ice mobility category describing homogeneous ice conditions (similar composition of partial concentrations by ice thickness and floe size) delineated into a single area (polygon). When setting up detection rules and procedures for operators, care was taken to ensure no second meaning or possibility to misread definition were available. Automated quality assurance algorithms inbuilt in the system ensure data consistency and timely reminders to operators pointing them to the areas of outdated observations. The following categories were thus introduced:

1. Mobile category contains polygons in the area with drifting ice. Comparison with adjacent in time images clearly shows ice displacements of distinctive floes, cracks, and other recognizable features. Most drift displacement observations are recorded in the areas where mobile ice is recorded. Ice hazard assessment for structures and operations sensitive to ice movement will contain most effects based on duration and persistence of mobile ice in the area of interest. For example, lighter vessels being affected with side drift while in confined dredged channel may be pushed off the channel to ground in surrounding shallows. The percentage of season duration in mobile conditions can be derived from the dataset for a point of interest. Applying additional filters based on drift speed and direction characterizing unfavorable conditions for operations one can estimate potential downtime for channel's layout.

2. Stationary categories are the areas that were recorded mobile previous day, but comparison to the current analysis shows no evident displacements as described above. It is not evident for that day of analysis, if the area is stabilized or there is just not enough wind force, or the direction is not favorable to initiate drift. Areas with this attribute are an intermediate stage between mobile and other mobility states. As there are no evident signs of ridging and

destroyed floes it is not possible to state that compaction takes place, but at the same time there still can be some pressure in the area, but just not enough to cause ice cover deformation. This grey area poses hazard to fixed structures because the worst-case loading scenario at slow speeds can be experienced with ice loading taking place in creep mode exerting higher loads.

3. Semi Stable category is assigned when the previous situation persists for three days, but there was still no evidence that wind with sufficient force to cause drift in favorable direction occurred to initiate drift.

4. If an area did not move for more than 5 days and/or there is evidence that there was sufficient force wind in favorable direction the area is assigned stable category. Areas with both stable categories assigned may still expose deployed marine units or structures to ice loads under strong wind conditions. Very small-scale ice cover displacements (under 50 m from 2014 onwards and under 150 m for earlier periods) may still occur, but no continuous crushing associated with ice movement is possible. The duration of stable ice conditions is important for port station keeping during cold spell periods. This is when operations in the port area generate significant volumes of brush that may reach intolerable thickness.

5. Compacting category is assigned to areas with evident signs of ice cover deformation. These areas have a direct impact on transportation. Reduction of transit speed due to necessity to ram ridges or increased transit time necessary to take a detour around heavily ridged areas are the consequences for conventional ice breaking vessels. Excess side pressure when caught on surprise may lead to full stop with high potential to experience impact from pile-up on deck. Tactical planning of daily marine routes may include advice to traverse the area delay transit to future if adverse conditions are foreseen to expire in the weather forecast. Strategic planning based on the history of compaction can be used to define layout of dredged channels to avoid or make use of naturally forming ridged areas for protection from cross-drift.

Where favorable wind direction to initiate drift is mentioned it is normally the direction that moves ice seawards or towards neighboring areas with lower concentration or ice with significantly lower ice thickness. Following the logic, an unfavorable wind direction is towards coasts or stable ice areas. Such winds will normally result in compacting or stationary ice conditions depending on wind force.

Daily temporal resolution of mobility observations is sufficient frequency suitable for dynamics of the phenomena that enables investigation of causes and triggering mechanisms based on metocean conditions. Coarser resolution, however, will lead to high potential missing destabilization events and associated weather conditions.

DATA STRUCTURE AND TOLERANCE

Ice mobility is an integrated part of ice cover classification database of daily ice cover classification as described by Vernyayev et al. (2023a). The database may be connected to other data sources either through time or geographical reference. This integrity enables building and deriving statistics based on complex algorithms with multi-conditional filtering or relationships.

Figure 1 illustrates daily time series of mobility categories coverage composition over one of the northern forecast zones in the Caspian Sea illustrating difference between mild and moderate ice season. Associated wind conditions and observations of drift illustrate the tight relationship between the cause (wind) and effect change in mobility categories composition.

As data acquisition and monitoring program for the hindcast initiative is based on remote sensing data reliability of the dataset is high for the period from 2014 to now when high re-attendance by satellite platforms with free access to data was achieved with launch of Sentinel-1 program. Quality of observations during earlier years when Envisat and ERS program data was collected have also benefited from availability of all-weather SAR (Synthetic Aperture Radar) data. Informativeness rating defined with coverage by SAR data and degree of cloud cover impact on optical images was maintained to track reliability of recorded data for each forecast zone in the Northern Caspian. Similarly regular record of gaps between images was logged to keep track of modelled/observed entries into the database. This quality information is available online with free access (ICEMAN.KZ) alongside key climatic indexes for ice cover in the Caspian Sea.

Figure 1 Development of ice cover composition by mobility categories in a Caspian Sea forecast zone as observed during moderate (top) and mild (bottom) seasons during the period of available observations.

CASPIAN SEA MOBILITY

Ice cover mobility observations were collected for the whole Caspian region for the period from 2005 to 2023 together with ice cover classification during hindcast program as described by Vernyayev et al. (2023a). Resulting values were aggregated into a 1×1 km grid with all other parameters describing ice cover. This grid was used to aggregate statistical products presented below to describe mobility of ice cover in the region.

One of the most frequent queries that is considered during offshore operations reviews in reference to deployed crafts and offshore structures is to find out if initial assumptions based on observations in early 2000s are still valid. The general approach for qualitative analysis is associating considered event types or phenomena and their frequency to freezing degree days accumulated over an area of interest. This approach is subjective depending on availability of reliable records and observations. Most importantly it does not consider dynamic processes associated with wind regime and ice drift.

The hindcast database that now reaches the early exploration period contains multiple parameters that in combination can be used as a detailed description of virtually any event or phenomena that may be encountered during offshore operations. Ice cover mobility is one of these parameters that serves as controller defining frequency or persistence of events. Ice cover mobility is geographically and temporally connected to ice thickness, concentrations, and coverage. The latter, when aggregated over a zone or region for a season period, form Ice Volume and Coverage indexes. These high-level indexes describe ice season severity with consideration of both thermal and dynamic processes with more details summarized by Vernyayev et al. (2023b). There is an obvious trend towards reduction of ice volumes generated in the region during the considered period. Freezing degree days (FDD) record associated with air temperature observations has longer observation history as illustrated in the same article and similarly demonstrates significantly warmer seasons recently. Further presentation of ice cover mobility is segregated into two periods with 2013 being a cut-off for previous colder seasons and milder ones experienced during the last ten years.

With this perspective in mind the following Figure 2 on the left illustrates ice cover mobility categories as annual probability of occurrence based on the two periods. Sum of Annual probabilities for occurrence of ice cover with mobility observations and open water equals 1. Probabilities are assessed over a 1×1 km grid for each cell and for duration of season from November 1 to April 15 to account for shorter and longer ice seasons. The first period considered is for the whole period observations from 2005 to 2022. This is how one would compile a statistical product for an engineering project regardless of the latest experience with milder seasons. The second period is from 2013 to 2022 when milder seasons only were observed. Note mobility records for 2022-2023 period were still going through quality assurance at the time of drafting this paper.

Propagation of higher values of open water probability into central basin of the northeastern Caspian as observed during the period of recent warm winters is the first most obvious impact. Practically it means that operations were less exposed to impact from interaction with ice. Persisting warming of the regional climate is likely to increase this propagation spatially. It is worth mentioning here that there is minor difference between the two periods along the northeastern coastline. This area is normally landfast as mostly affected with Siberia cold air intrusion events. The thickest ice cover with the highest concentrations persisting for the longest part of each season is observed here.

Area by probability of mobile ice cover occurrence categories has also increased significantly for the warmer period expanding towards surrounding shores from the central deepest part in the northeastern part of the sea. Structures and operations sensitive to drifting ice have experienced interaction with sea ice more often during the last ten years. Considering increasing frequency of open water occurrences as discussed above, increasing probability of mobile ice cover occurrences can only be achieved due to reduction of immobile ice cover comprising stable semi-stable and stationary ice. This reduction is illustrated with the last charts on the figure. The interesting effect of increasing number of artificial islands and structures at Kashagan can be observed in the Northeastern part of the sea where area coverage with higher probability of immobile ice has increased between Kashagan and Northeastern coastline despite of more mobile ice cover in the region.

The same figure on the right illustrates the evolution of mobile and immobile ice annual probability of occurrence based on observations during three discrete periods. Note increasing intensity and spatial coverage and coverage of mobile ice probabilities through history with earlier colder seasons on top and warmer ones in the bottom. The darkest areas in the latest summary for the period from 2017 to 2022 correspond to the locations where vast leads usually open with strong Easterly wind events.

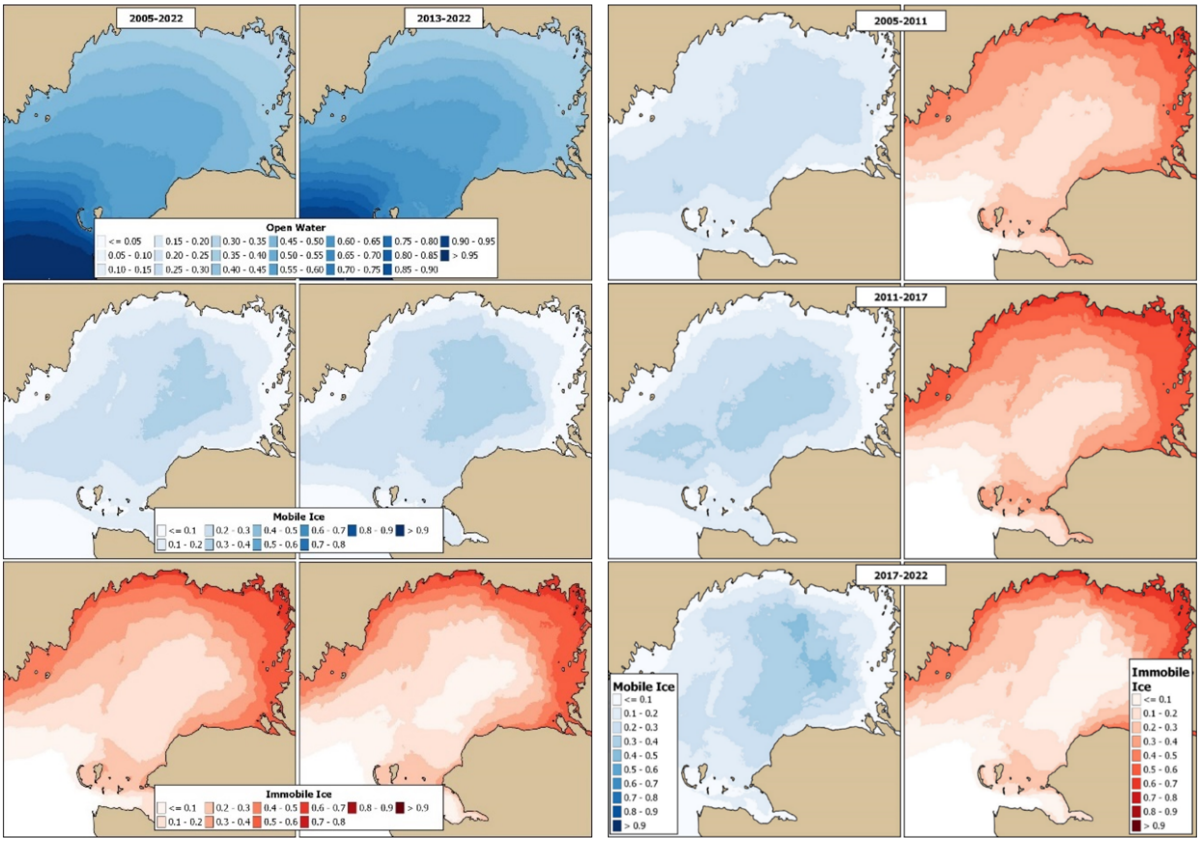

Figure 2 Annual probability of occurrence for observed categories of mobility for 2005-2022 and 2013-2022 periods (left) and for observed mobile and immobile categories for three subsequent periods from 2005 to 2022 (right).

Ice cover compaction as described above with intensive ice cover deformation was observed at a lot smaller frequency than the other mobility states (Figure 3). Probability of occurrence based on 10- or 15-years data rarely exceeded 1%. Note the effect of changing climate conditions on the location with higher probability of this phenomena. Compacting was more often observed in the Kalamkas area closer to the basin's Southern coastline during the colder winter. Higher frequency of observations has shifted to the Northern Coast west of Volga Delta with recent warmer seasons. It should be noted here that continuously falling water level might also have considerable influence on compaction with increasing number of anchor points becoming noticeable in different areas of the sea. More factors controlling ridging processes and comparatively rare frequency of occurrence require more observations (complete seasons) to derive reliable relationships between multiple parameters.

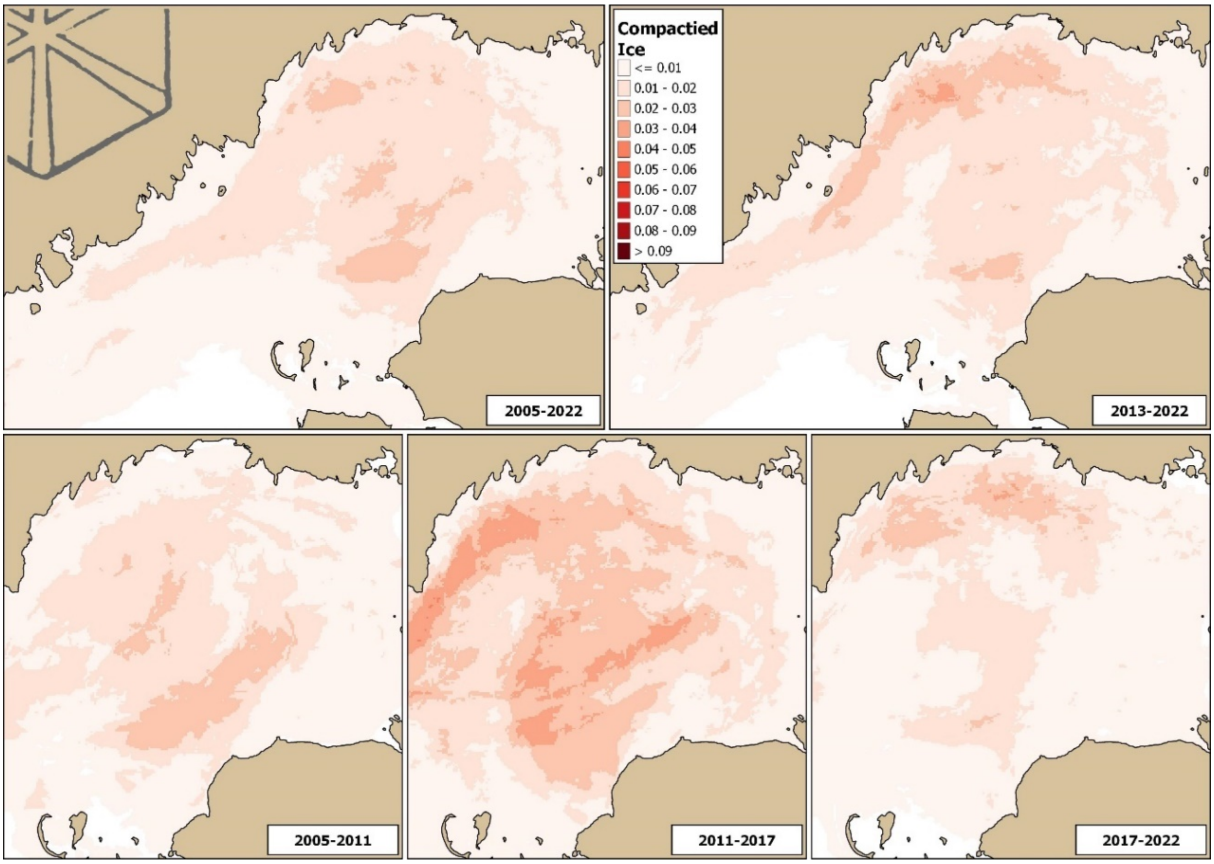

Figure 3 Annual probability of occurrence for observed compacted ice for 2005-2022 and 2013-2022 periods (top) and for three subsequent periods from 2005 to 2022 (bottom).

Temporal distribution of mobility observations over a zone of operations enables scheduled mitigation measures planning for each month of a season to control hazards associated with each individual mobility group. Figure 4 illustrates such monthly summaries for two forecast zones in the Northeastern part of the sea as delineated by Vernyayev et al. (2023a) based on observations from 2005 to 2022. Depending on proximity to coastline and month a season predominant conditions vary by the area coverage. This variation allows phased and differentiated resource planning of either operations to suit favorable conditions or optimized scheduling of mitigations means mobilization.

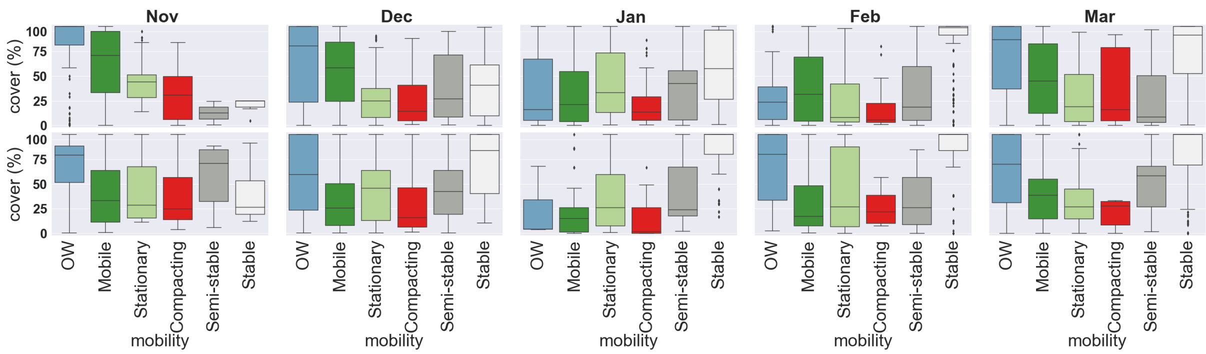

Figure 4 Mobility distribution by month for the period from 2005 to 2022 in two northern forecast zones of the Caspian Sea.

The short analysis presented above is the simplest example and a showcase of mobility dataset application for practical analysis to support data driven decision making in ice covered waters. The following section illustrates other ways to apply mobility information.

OTHER APPLICATIONS

Ice cover mobility data applications vary a lot by the type of analysis it is useful to enhance. This can be anything from facilitating operational monitoring and forecasting to closing gaps in reliable observations to serving a filter for scenario-based probabilistic assessments for engineering purposes.

Ice Cover Behavior Modelling during Ice Charting

Mobility category is useful to supplement modelling ice conditions during operational ice charting support when there are no images available for a day of analysis. Operators can concentrate on previously mobile areas to assess changes in ice cover that may occur with observed weather. Whereas immobile conditions may only be verified against threshold wind forces to check if there is possibility for destabilization of ice cover. Vernyayev et al. (2023c) have developed cross-correlations between weather observations and effects on ice cover with various concentration and thickness for each mobility category. This approach enabled quantitative data driven decision making in response to operational queries.

As an example, thick ice that stabilized a few days ago during a cold spell will become mobile in case of strong wind or few days of mild temperatures. On the other hand, ice areas in shallow waters with many grounded ice rubble features will unlikely displace for duration of the whole season until break-up. Statistics of ice cover behavior over locations in the region help perform this hazard evaluation through a season based on short- and medium-term forecasts.

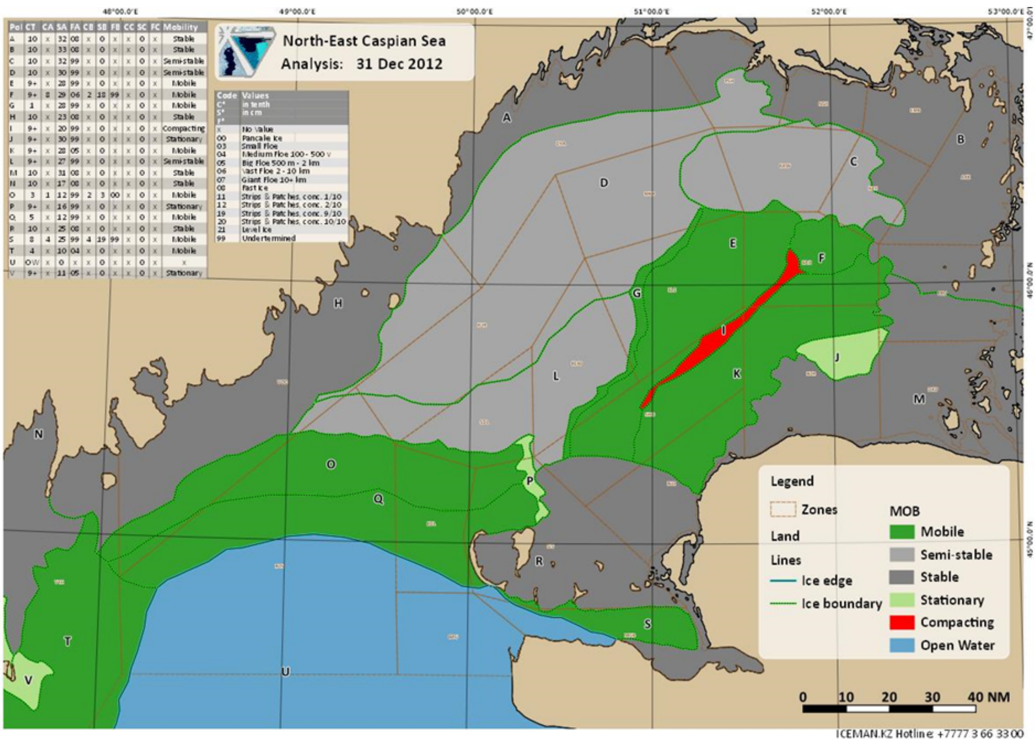

Figure 5 Sample ice cover mobility chart from the operational interface driving operators attention towards compacting and mobile areas in the Northeastern part of the sea.

Ice drift modelling

Ice cover mobility observations were useful to enhance ice drift modelling applications. The method of drift modelling based on wind data and ice displacements from remote sensing data as described in Kadranov et al. (2017) was enhanced with introduction of modelled drift to fill gaps between observed displacements. Previously, the number of ice displacements for analysis depended on the number of satellite images and the ability of operator performing the analysis to detect and digitize those displacements. The resulting drift datasets were intermittent both spatially and temporally. Descriptive statistics and insights based on the data were misleading towards the bias introduced by the skill of ice charting operators, frequency and quality of satellite images and other factors that could not be accounted for with an obvious correction algorithm. The completeness index in the Figure 6 below shows the ratio of days with such observations versus the number of days in mobile ice conditions.

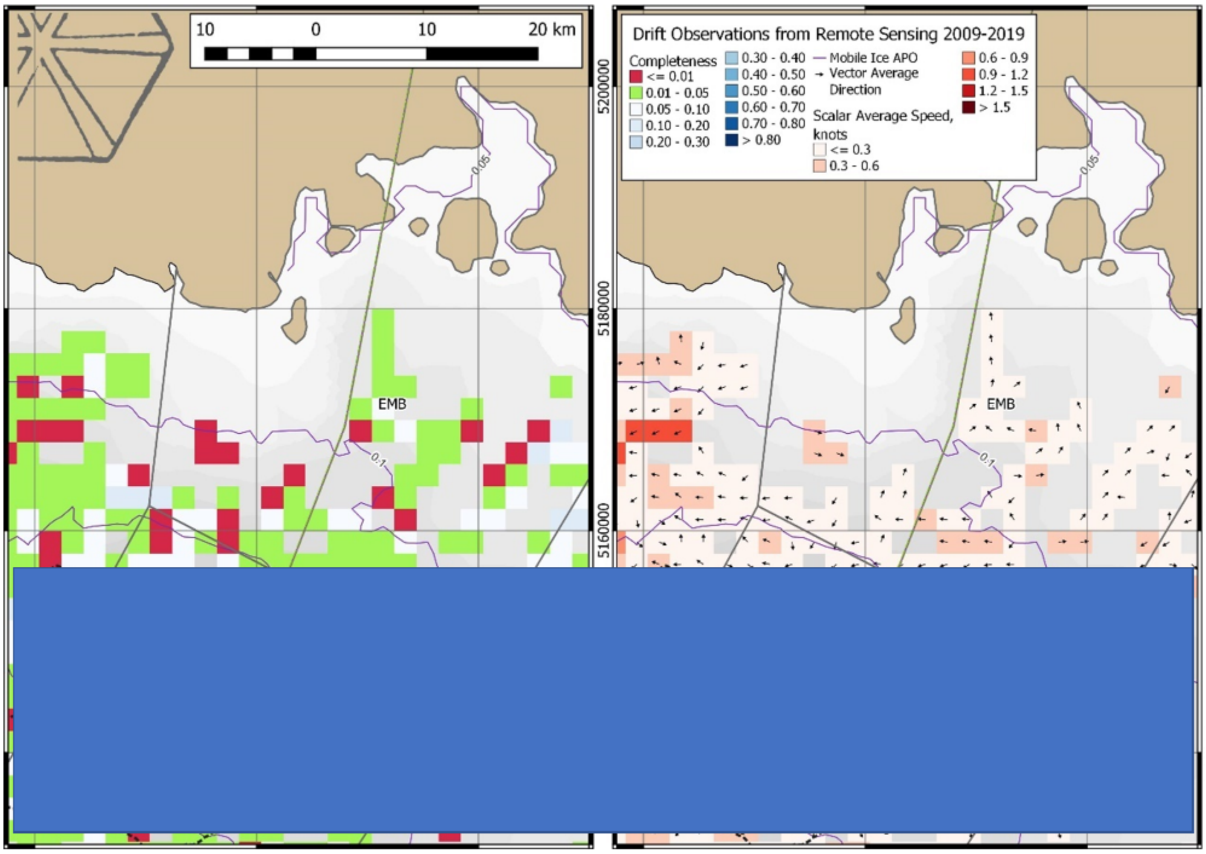

Figure 6. Spatial distribution of drift observations derived from filtered remote sensing data. Completeness index (left), daily average vector speed and direction-TO (right) in mobile ice conditions.

An introduction of intermediate step building wind to drift regression model and applying it to grid within mobile ice areas for each day of observations using gridded wind data as an input enabled creation of complete modelled ice drift dataset with removed bias. The accuracy of the dataset in this case is only limited with the number of displacement observations enabling classification by different geography of ice conditions and persistence of wind events. Regression models with such classification are challenging to build mainly due to the lack of observations. Insufficient number to build a reliable model for rare combination of conditions being the most difficult task.

Probabilistic Ice Loads

Ice mobility category can be used for engineering purposes. Development of probabilistic ice load estimation model is not trivial. Its main goal is to account for coincidence of various factors and to exclude simultaneous action of two factors at their extreme level if that does not occur naturally. Scenario of ice-structure interaction may include ice thickness and concentrations, strength varying with air temperature, water level variation to define elevation of applied loads and onwards to make analysis as detailed as available data allows. Ice movement is one of the most important conditions for ice loads to be applied to the structure. Thus, ice cover mobility can serve as a filter for previously observed ice and metocean conditions. Figure 7 illustrates global ice load variation on a narrow structure through the course of a season in two neighboring forecast zones of the Northeastern Caspian based on observations of ice conditions when they were recorded mobile in the period from 2005 to 2022.

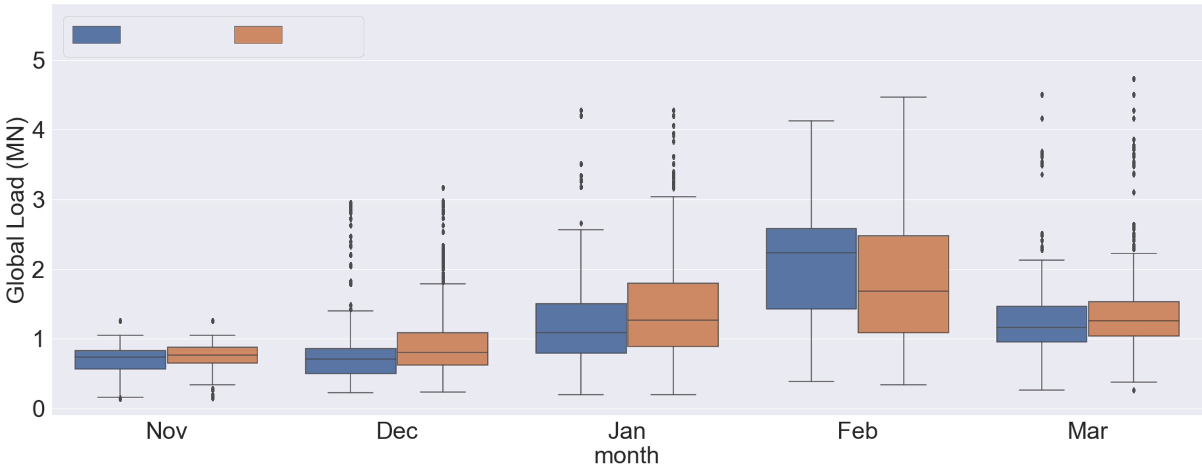

Figure 7 Monthly development of global ice load on a narrow structure for period from 2005 to 2022 as derived for two distinct forecast zones (blue – offshore with mobile ice conditions orange – pre-coastal with dominating stable ice cover) in the Northern Caspian. See Dutoit (2012) for box plot visualization of quartiles.

Ice Cover Destabilization Forecast

The date of ice drift initiation is a key challenge to manage ice hazards to operations in areas with temporarily immobile ice. Forecasting such events is based on wind threshold. However, there is significant variation of threshold observations in regions like Caspian with account for interannual variation of ice cover development and through ice cover properties spatial distribution. Finding patterns and controlling factors here is a difficult data management task first of all. Ice cover classification hindcast database with multiple parameters was originally designed to resolve lack of input for this type of analysis. Tracking coincidence of weather and ice conditions that lead to ice cover destabilization or, in other words transition from immobile state to mobile state allowed defining wind threshold for such events as discussed by Vernyayev et al. (2023c) in more detail. Further sophistication of the basic model discussed in the article with introduction of classification by additional factors into the regression analysis.

CONCLUSIONS

Ice cover mobility was presented as an event frequency indicator for the Caspian Sea that can be used to facilitate ice cover impact assessment on structures and marine operations. A short discussion on correlation of Mobility with climate related indexes illustrates quantification of recently observed climatic trends in the region with effects on frequency of events that may impact operations.

Some examples of applications for the use of mobility data were briefly introduced. Empirical models of ice movement initiation and ice drift forecast in support of marine operations benefit from more accurate classification of data to build correlations. Probabilistic models for load estimation on structures and downtime analysis of operations benefit from more detailed and accurate quantified description of events.

Further potential of the dataset is to be unveiled through the course of future research and other applications. Combination of ice cover concentration, thickness and mobility with other datasets including metocean observations of air temperature, wind and water level, other ice observations like drift observations, stamukhi records and ice cover deformation ensure structured approach to delivering data driven analysis.

REFERENCES

Dutoit S. H. C. 2012. Graphical Exploratory Data Analysis. Springer.

Bukharitsin P., Vernyayev S., Sigitov A., Kadranov Y., Bukharitsin A., 2019. Marine Operations in Channels through Shallow Ice-Covered Waters. *Proceedings of the 25th International Conference on Port and Ocean Engineering under Arctic Conditions*. June, Delft, POAC19.

ICEMAN.KZ [online]. Available at: https://www.ice-service.net/ru/caspian-sea [Accessed 01 March 2023].

Kaartokallio, H., Granskog, M. A., Kuosa, H., & Vainio, J. (2016). Ice in subarctic seas. *Sea Ice: Third Edition*, 630–644. https://doi.org/10.1002/9781118778371.CH27.

Kadranov Y., Sigitov A., Vernyayev S., 2017, Comparison of satellite imagery based ice drift with wind model for the Caspian Sea, *Proceedings of the 24th International Conference on Port and Ocean Engineering under Arctic Conditions,* June, Busan, Korea, POAC17.

Vernyayev S., Kadranov Y., Sigitov A., Vernyayeva I., 2023a, Caspian Sea Ice Cover Hindcast Database. *Proceedings of the 27th International Conference on Port and Ocean Engineering under Arctic Conditions*, June 12-16, Glasgow, UK, POAC23.

Vernyayev S., Kadranov Y., Sigitov A., Vernyayeva I., 2023b, Caspian Seasonal Ice Volume Trends in the Recent History. *Proceedings of the 27th International Conference on Port and Ocean Engineering under Arctic Conditions*, June 12-16, Glasgow, UK, POAC23.

Vernyayev S., Kadranov Y., Sigitov A., 2023c, Caspian Ice Cover Destabilization Wind Threshold. *Proceedings of the 27th International Conference on Port and Ocean Engineering under Arctic Conditions*, June 12-16, Glasgow, UK, POAC23.

WMO, 2004, SIGRID-3: A VECTOR ARCHIVE FORMAT FOR SEA ICE CHARTS. World Meteorological Organization, WMO/TD-No.1214.

WMO, 2014, WMO Sea-Ice Nomenclature. World Meteorological Organization. WMO No.259.