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Ice gouging pattern on the Northern Caspian derived from SAR data.

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ABSTRACT

Ice gouging in the Caspian Sea has been studied for a long time for constructing and operating underwater pipelines from oil and gas fields to the land. Last time we defined the areas of stamukhi localization and presented a big picture of Caspian shelf zonation according to ice gouging intensity. Stamukhi are a terminal stage of deformed ice evolution, forming stable ice features affecting the bottom. Nevertheless, all kinds of deformed ice can interact with the seabed leaving ice scours behind. New data on the degree of ice deformation from SAR image interpretations allowed us to improve the prediction of ice gouging intensity and ice scours formation all over the Northern Caspian.

KEY WORDS: Ice Scours; Ice Ridges; Seabed; Remote Sensing.

INTRODUCTION

There was a lot of ice gouging studies performed in the Caspian Sea during the recent years. Majority of the studies were targeted for design and construction of underwater pipelines from oil and gas fields to land to define safe burial depth. Croasdale et al. (2004) described field research program to address engineering issues in the Northeastern part of the Caspian with a lot of attention to seabed impact from interaction of ice. Fuglem et al. (2013) added more details on the design parameters of ice scouring in the region. Both works characterize commercial activity associated with development of infrastructure offshore in the Kazakhstan sector of the sea. Maznev et al. (2020) presented a bigger picture with charts of ice gouging intensity for the entire Northern Caspian depending on the severity of winters. These charts are based on the air reconnaissance data, digitized lines of ice coverage development (Ogorodov et al., 2020), analysis of stamukhi distribution (Sigitov, Kadranov and Vernyayev, 2019) and water depth with focus on obviously grounded rubble features like stamukhi as indicators of interaction intensity with seabed. The latter were identified as a logical terminal stage of ice cover deformation process, forming a static ice rubble feature grounded to seabed and forming a deep pit underneath. They are comparatively a rare but the most intensive hazard to seabed structures.

Other types of deformed ice such as ridges and floating ridged areas that are a lot more frequent and mobile may interact with seabed leaving ice scours behind. Ice ridges and their spatial distribution were rarely studied in the region. Digitized records of air reconnaissance observations are scarce and difficult to analyze. Deformed ice coverage derived from SAR image interpretation (Kadranov, Vernyayev and Sigitov, 2023) fills the gap of missing data to verify earlier findings and improve resolution of ice gouging impact charts. This verification will improve prediction model of ice gouging intensity and ice scours formation all over the Northern Caspian.

This article discusses new data source exploration as a first step and a verification trial based on new data acquired in a focus area around Kashagan field as shown in Figure 1. The area is economically active and conditions authors to maintain readily available datasets for analysis in support of engineering and operations.

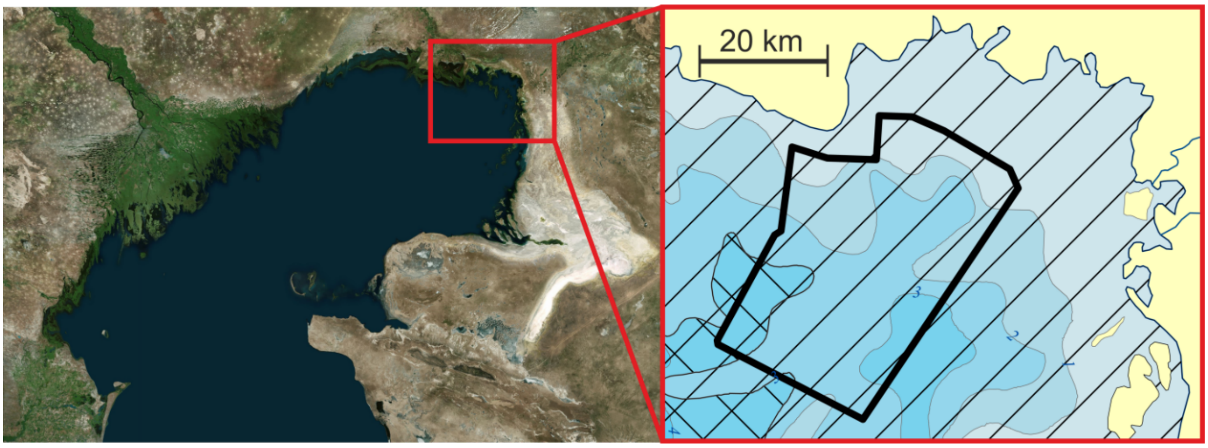

Figure 1. Study location on the Northern Caspian. Cutaway shows the study area in bold line and ice-gouging intensity zones according to (Maznev et al., 2020): diagonal hatch is a fast ice zone, diamond shading is the zone of fast and drifting ice interaction.

METHODS

Deformed ice gives a high backscatter on SAR images acquired from space. Kadranov, Vernyayev and Sigitov (2023) applied unsupervised analysis of SAR data using k-means algorithm allows for automatic detection and segmentation of areas with low medium and high deformation. The algorithm iteratively partitions an image into clusters by minimizing variance within cluster. Authors processed Sentinel-1 data for eight winters from 2014 to 2022, filled gaps between observed images with interpolated data identifying change of deformed ice coverage with deformation event scenario filtering their ice and metocean database Vernyayev et al. (2023a) and delivered season average deformed ice categorized by intensity coverage for a 1×1 km grid by season in the area of interest. Deformed ice classification comprised undeformed, semi-deformed and deformed categories as illustrated with sample interpretation in the figure below (Figure 2).

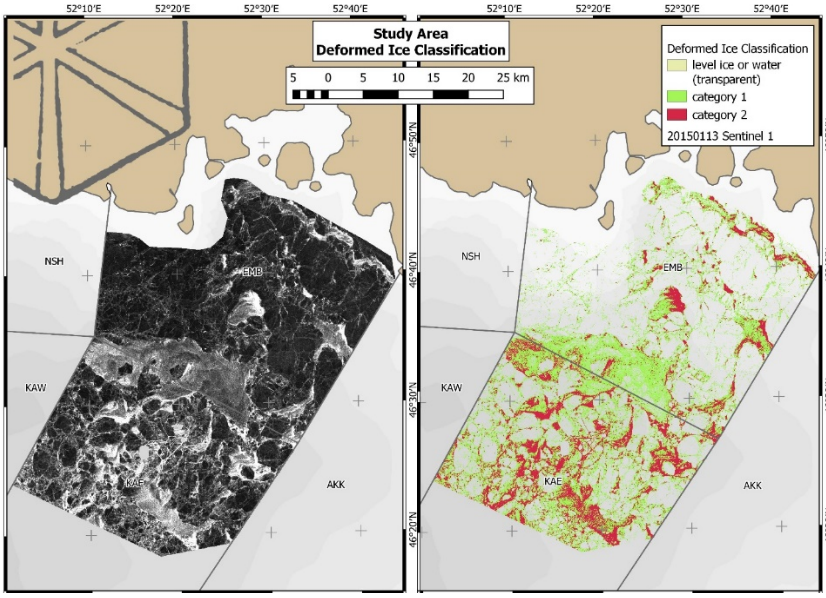

Figure 2 Sample Sentinel-1 image classification with two distinct categories of deformed ice cover by Kadranov, Vernyayev and Sigitov (2023).

Considering the area of interest is very shallow under 3 m with gentle slope towards the northern coastline it is a valid assumption that deformed ice areas derived from SAR are covered with ice ridges and hummocks. With water depth being so shallow sufficient keel depth that can interact with seabed is very likely to occur in deformed areas with high coverage of a grid cell. At this stage of exploratory studies expert opinion was used to assign keel depth based on assessment that was developed for the estimation of the ice-gouging intensity by Ogorodov et al. (2013) and later confirmed with observations by Ogorodov et al. (2020). This is considered sufficient for the purpose of this study. Further confirmation of keel depth correlation to the combination of coverage and category of deformation in the new data is yet to be confirmed with field data in future. Deformed ice distribution patterns were analyzed for each of the seasons separately to enable classification by winter severity.

Winters during the available data period were segregated into classes by their severity using cumulative freezing-degree days (CFDD) and ice volume statistics Vernyayev et al. (2023b). This classification allowed averaging the data by season types and show zones with different intensity of ice impact on seabed, as well as comparing obtained data with previously proposed charts for mild and moderate winters (there are no severe winters in the period 2014-2022).

RESULTS

The study area is in the Northeastern part of the Caspian. It is situated in the marginal zone between normally stable and normally mobile ice cover as illustrated by Sigitov et al. (2023). Developing Kashagan field and increasing number of artificial islands in the area adds to increasing stability of ice cover in the area. Water depth in the area varies from from 0.5 to 3.5 m. Being mostly 2-3 m it is subject to mostly negative and positive wind induced water surges and interannual reduction of about 5 cm per year as observed with satellite altimetry by Chen et al. (2023).

According to our earlier estimations, this area belongs to a fast ice zone that can be described as limited scour impact of ice features, ice ridges and grounded hummocks. The intensity of ice gouging here is determined with low likelihood of fast ice displacements. Bottom scouring by ice floes with ice ridges frozen into them occurs during the fast ice break-up by the end of season. The south-western part of the area belongs to the zone of combined fast and drifting ice interaction during mild winters as shown in Figure 1. It is characterized by intensive scour impact on seabed with ice ridge keels forming along the boundary of fast ice. Recently released more detailed data on occurrences of ice cover mobility is yet to be applied to our models for further increasing precision.

Figure 3 illustrates variability of deformed ice coverage by concentration in each grid cell, spatial distribution of occurrence frequency and most importantly significant difference between seasons with different severity rating.

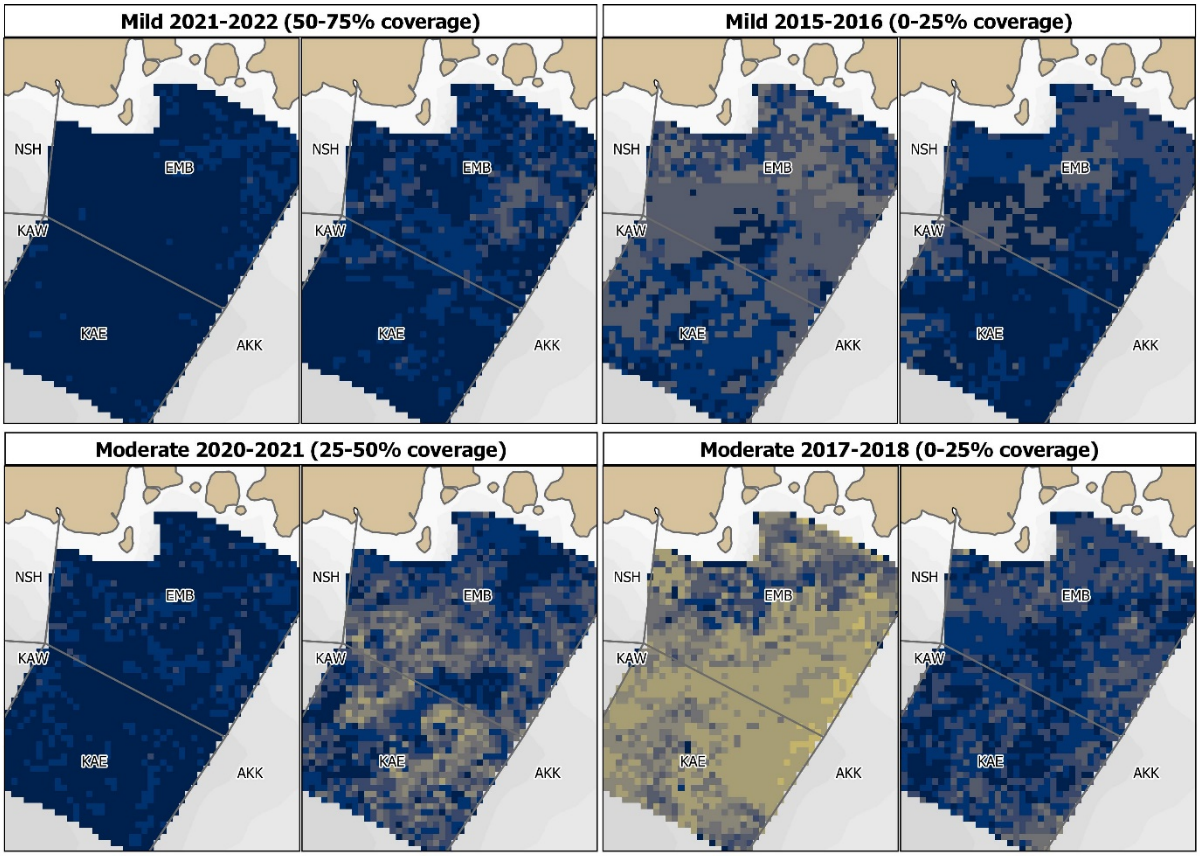

Figure 3 Spatial distribution of seasonal average deformed ice coverage with varying concentrations per grid cell for random seasons during the period of observations by Kadranov et al., 2023.

Detailed deformed ice coverage over the study area was generalized to be comparable with large scale output of our prediction models. Figure 4 illustrates resulting simplified contours of combined high coverage and occurrence frequency of deformed ice category that was defined to have high likelihood of sufficient keel depth capable to scour seabed. Intensive ridging occurs every season in the area. Variation of coverage and location forms the difference between the seasons to define patterns describing correlation to winter severity.

Newly generated charts were used to create schemes of ice gouging intensity with classification based on winter severity as shown in Figure 5. We distinguish zones of the lowest (1), moderate (2) intensive (3) impact on seabed from deformed ice cover.

There were 4 mild and 4 moderate seasons during the period of available observations from 2014 to 2022. The dataset as well as the recent history does not include severe seasons as discussed with ice volume trend analysis. Resulting distributions indicate the intensity of impact There is no area where the most intensive ice effects by season were presented four times within the same season category by severity.

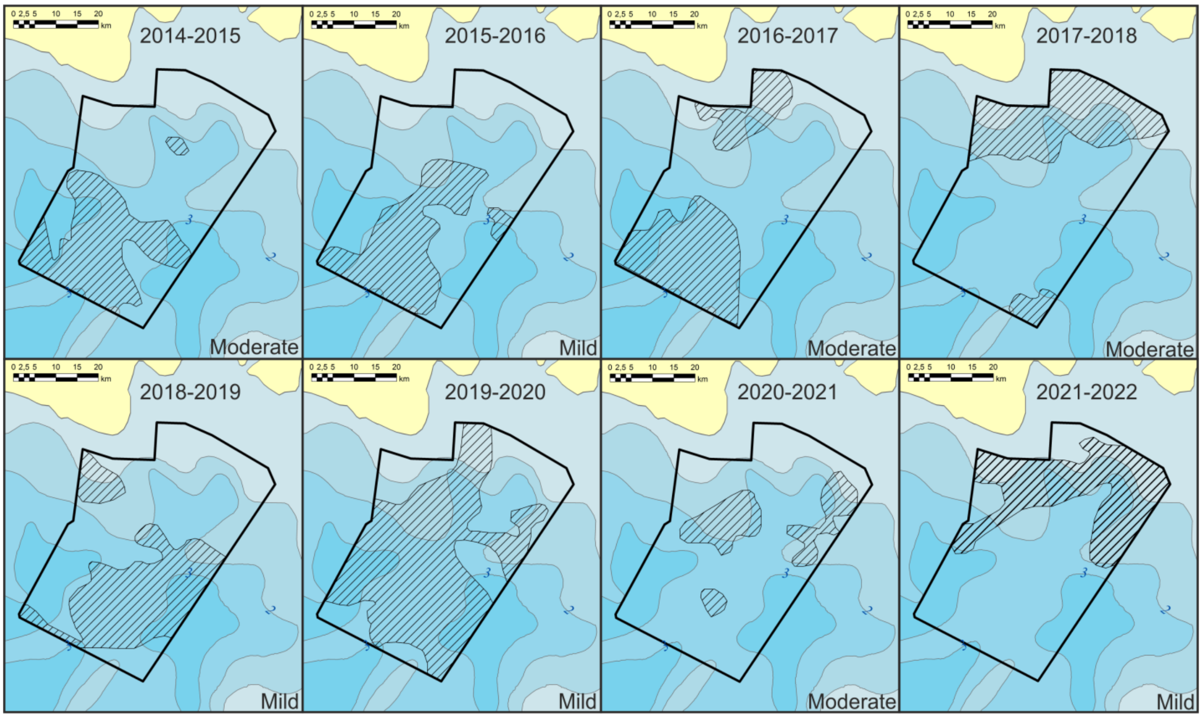

Figure 4. Areas of most intensive ice effect on the seabed in 2014-2022 by season shown in hatch.

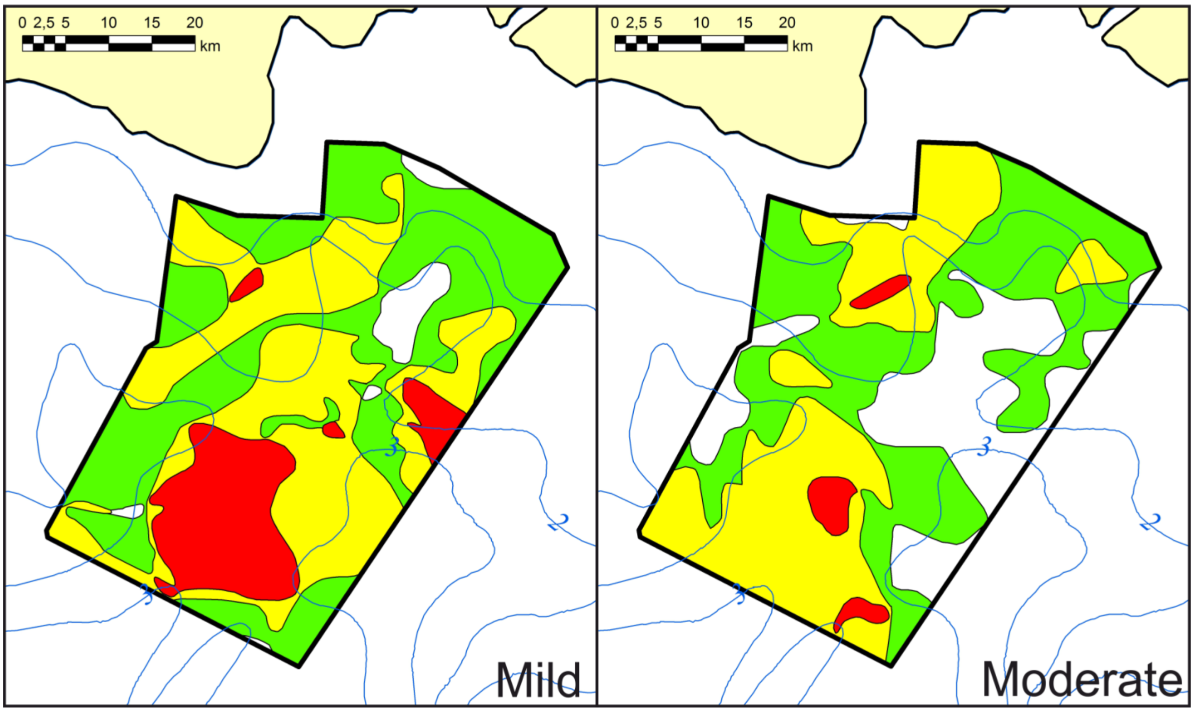

Figure 5. Ice gouging intensity in the study area by the severity of winter seasons. Green shows zones of the lowest ice impact, yellow – zones of medium intensity, red – zones of the most intensive effects.

DISCUSSION

Exploration of the new dataset did not any patterns in the distribution of impact severity on seabed in the area depending on season severity. Chaotic character of the ridge formation phenomena regardless of season severity could be a potential reason behind this. Missing more detailed information on the vertical component and correlation to deformed ice coverage and intensity could also explain our inability to define such patterns at the first approximation and motivating for further study in this direction. Outlined areas with higher and lower likelihood of deformed ice occurrence depending on seasons development. Considering the depths throughout the study area are shallow and the degree of observed deformation, the impact of ice on seabed is very likely. Assumption that this impact is different depending on seasons severity enables ability to build a prediction model defining areas with likelihood of scours formation. The model connected to high level climate indices is important to facilitate climate change impact assessments and long-term operational planning of scour related mitigation measures.

Ice cover being softer and breakable with warmer air temperature persisting over milder winters contributes to more active ice deformation and hummocking. Recently observed trend towards further warming of the region confirmed intensification of ice cover mobility in this area with recently acquired data. Sigitov, Kadranov and Vernyayev (2019) have evidenced most of the stamukhi near the coastline formed during mild winters, and the most intense ridging and stamukhi formation were observed in the fast ice zone. Milder temperature conditions provide a smaller thickness and strength of the ice. In special wind conditions, fast ice undergoes short drifting events, which contributes to active ridging. The area of landfast ice in mild winters remains quite extensive, which creates conditions for hummocking and stamukhi formation over a large part of the water area despite it being stable in general for duration of season. Among other things, this suggests that the intensity of ice-gouging processes in the fast ice zone has been increasing in recent years (Maznev and Ogorodov, 2020).

Previously presented data on expected ice impact is obviously too coarse and generic needing further enhancement to account for details on local scale. Using SAR data and newly acquired data is the key to obtain this detail and with similar analysis performed across the entire North Caspian region will help to deliver the level of detail and precision to the prediction of the ice effects on the seabed. However, deformed ice data derived from SAR data should further be studied to define clearly regular patterns in its occurrence over the seasons.

CONCLUSIONS

Using a new technique of ridged ice spatial distribution analysis based on the processing of SAR images, we obtained new data source on the deformed ice coverage in the northeastern part of the Caspian. This allowed us to take a fresh look at ice-gouging patterns. So far, this method of input data acquisition for predicting the ice scouring impact in certain places has not been confirmed with direct application of previously developed algorithms nor it has not been extended to a large area of regional scale where we are used to operate our models. However, we believe that this data will be useful to deliver impact assessments on local scale where the level of detail matters most to design suitable protection of underwater pipelines and planning marine operations. Further adaptation of our algorithms to account for the new information study ice gouging areas for developing.

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