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Caspian Ice Cover Destabilization Wind Threshold

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ABSTRACT

Ice cover along the shores of the Northeastern Caspian stabilizes through the course of a season depending on severity, number, and duration of freezing and thawing events, wind conditions. Once stable ice zones develop, they persist growing in thickness and building up strength before break-up. Knowing wind speed threshold that leads to formation of cracks and leads or the whole area destabilization is critical for forecasting ice impact hazards to offshore operations. This article discusses definition of the threshold value based on ice cover mobility and wind observations.

KEY WORDS: Caspian Sea; Ice cover stability; Wind threshold, Ice forecast, Ice hazards Management.

NOMENCLATURE
ECMWF (European Centre for Medium-Range Weather Forecasts), ERA5 (latest climate reanalysis produced by ECMWF)

INTRODUCTION

Offshore operations in ice covered waters rely on accurate weather forecast and regular ice hazard assessment for specific structures and works. Precision of ice related hazard arrival time estimates is correlated first to the quality of weather forecasts in the part where applied models and weather monitoring systems are capable to foresee extremes. The other factor that controls quality of operational hazard evaluation is accumulated knowledge of ice cover response to weather conditions. The latter is the matter of proper data management originally designed to facilitate hazard identification and operational impact assessment in near real time. Precision of ice hazard impact assessment is essential in terms of effects on structures and arrival time to ensure adequate response and mitigation measures in time when it is needed. Most importantly, false alerts that have resulted in action increases cost of operations.

Northeastern part of the Caspian is subject to seasonal ice cover. Extensive offshore oil & gas activity relies on daily monitoring of ice cover development and regular assessment of hazards to offshore structures and operations. Variability of ice conditions from season to season and spatially across areas makes normal patterns of ice cover response to weather conditions hardly recognizable if not aided with sophisticated data management support. Changing environment that includes increasing frequency of mobile ice cover occurrences, continuously falling water level and decreasing ice thickness affect previously observed patterns with necessity of introducing trends accounting for the change to statistical models to increase their accuracy.

This article is dedicated to identification of wind and ice conditions combination that precede destabilization of immobile ice cover typical for an area in the Caspian. Analysis of ice and metocean factors for observed change from immobile to mobile state is critical to ice hazard evaluation. Accuracy of predicting the moment when previously stable ice sheet moves is critical for operations to use forecast response time effectively and implement corresponding mitigation measures.

While analytical solution of this problem based on the balance of wind stresses and resisting forces in ice cover is described by McKenna, Crocker and Croasdale (2023) this article demonstrates identification of wind threshold to initiate drift events from statistical point of view considering detailed records of ice and metocean observations and their coincidence in the period from 2005 to 2022. Analytical solution using the same data sources is discussed by McKenna et al. (2023).

DATA SOURCES AND EVENT CONFIGURATION

Derivative of ice cover classification dataset described by Vernyayev et al. (2023) summarized into a 2×2 km grid was used as a backbone for statistical assessment of cross-correlations across the whole region. The grid was compiled to contain all ice cover classification data including ice cover mobility classification as described by Sigitov et al. (2023a) and ice thickness variation by Sigitov et al. (2023b), bathymetry, water level by KazHydroMet that has recently become open source.

Immobile ice cover classification as recorded during hindcast activity comprises three different states of ice cover immobile conditions. These distinct stages were used in this study to differentiate derived threshold values to account for duration of potential consolidation that may take place over a zone on a macroscale.

Weather records were extracted from modified ERA5 data resampled to daily average for the purpose of this application. Wind data averaging mechanism included automated analysis of moving two-day average. Average and maximum wind speeds, average vector wind direction and variation sector corresponding to 50% of stronger wind in distribution were extracted for further use. Day’s definition was set to correspond with remote sensing data collection calendar in 00:00 UTC to ensure wind event that caused destabilization of ice cover the day before local time morning SAR (02:00-03:00 UTC) is captured with the last day of previous condition observed.

ERA5 and ECMWF operational forecast have extreme events underestimated on hourly level as normally happens with modelled reanalysis or forecast. Underestimation may reach up to 5% of the observed wind speed with ground stations. Having that in mind statistical outputs from the exercise with threshold definition based on ERA5 record as input are compatible with ECMWF operational forecast. Daily averaging is also expected to dissipate the error observed on an hourly level.

Figure 1 illustrates time series of wind speed observed during a sample ice cover destabilization event observed in a grid cell of the Northeastern part of the Caspian. Distribution of wind speed by direction (TO) based on the two days of observations data illustrates derived aggregates describing destabilization event from the weather driving perspective. Grey sectors in the distribution are 50% lower wind not defining direction of acting wind.

The level of attention to identify direction of acting wind forces is justified with variability of ice cover response to wind action direction that was observed previously with modelling drift by Kadranov, Sigitov and Vernyayev (2017). Derived regression models to enable wind data driven forecast of ice drift have shown significantly lower response of ice cover to wind action in direction of obstacles. Coastline, areas with high concentration of artificial structures or grounded rubble features like stamukhi, stable ice zones can be considered as the examples of obstacles limiting drift speed and requiring more significant wind action to destabilize ice cover.

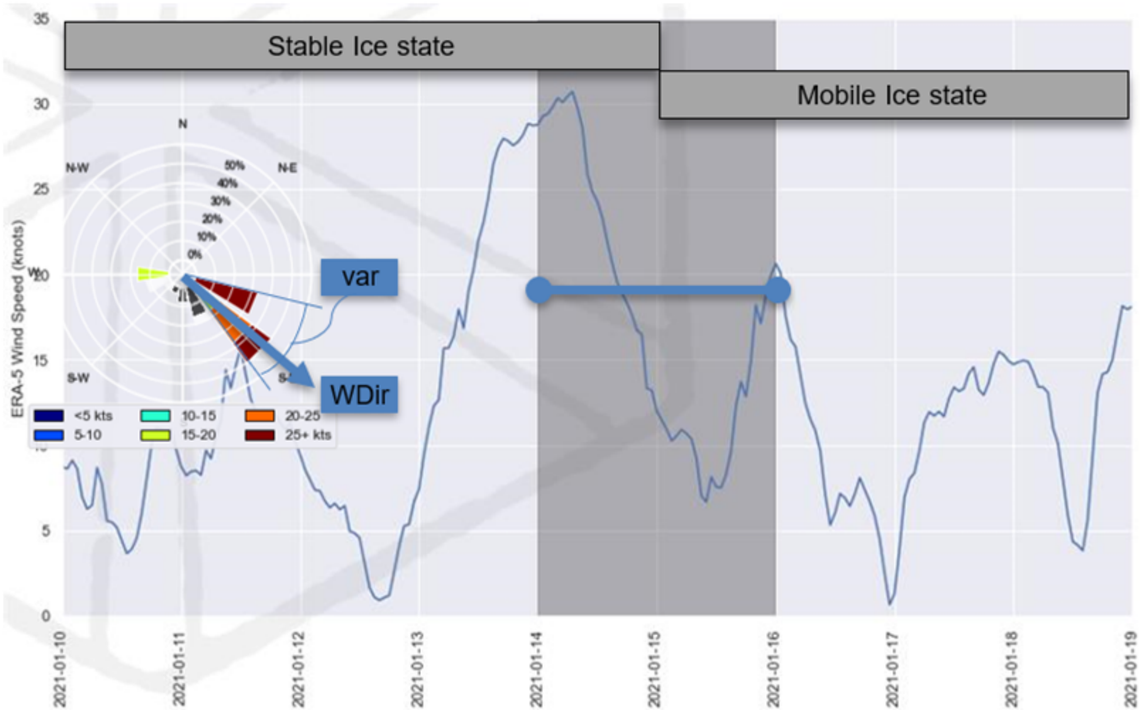

Figure 1 Sample destabilization event illustrating wind speed observations during transition from stable to mobile state at a point in the Northeastern Caspian. Wind rose for the two days of the event illustrates selection of prevailing direction (WDir) and variation (var) of stronger wind. Grey sectors in the rose are 50% lower wind not defining direction of acting wind.

Wind direction variability for the 50% strongest wind during an event was assessed with building distributions of direction deviation from average vector resulting from hourly observations. Distributions were built using Yamartino (1984) approach, where the 0°/360° (or ±180°) discontinuity is resolved with forced special consideration. For example, the directions 1°, 0°, and 359° (or −1°) do not average to the direction 180°.

In addition to cause-and-effect observations as described above dates of destabilization events for transition from distinct immobility state to mobile state in each cell were defined based on the records. Relative ice strength as a function of air temperature and weighted average ice thickness were estimated for each day during destabilization events. Fetch length was estimated as distance from cell to coast or border with open water or mobile ice conditions opposite to average direction (TO) of acting wind for each event. These event descriptors were added to each event record enabling classification, filtering, and identification of dependencies for event occurrence.

ICE COVER DESTABILIZATION EVENTS

Resulting number of events in each grid cell of sample forecast zones segmented by relative strength of ice achieved at the time of their occurrence is summarized with Figure 2. Thus, frequency of events as displayed in the plots is illustrative of the events scale both spatially through homogeneous grid and temporally through consistent and regular records. Roughly the same area of the zones makes them comparable in terms of effects to discuss proximity to coastline. Plots on the right were derived for a pre-coastal zone along the Northern shore to illustrate events in normally stable ice zone as observed through the years of existing record. The left plots are derived for adjacent forecast zone south of the above to illustrate marginal area where stable ice normally dominates by area and duration during severe and moderate ice seasons.

Figure 2 Count of destabilization events over grid cells by relative strength estimated for the time of occurrence forecast zones in the Northeastern forecast zones of the Caspian Sea. At Northern coast (right) south of the pre-coastal (left)

Qualitative description above based on feedback from observers and experience of operations in the region was confirmed with derived number of destabilization events in the mid-season corresponding to higher relative strength values. Overwhelming number of events correspond to occurrences when ice strength was estimated below 10% in both zones. Normally, considering ice strength estimation algorithm used in the hindcast program this range of values corresponds to long (more than two weeks) thaw periods or the end of season when observed air temperature is consistently near and above 0°C. The other ranges of occurrences from 10% to 30% and above 30% segment transition through moderate cold to cold periods. Note destabilization events in the history did not occur when relative ice strength was above 70%. The last is normally associates with significant cold air intrusion from the East or Northeast and are associated with strong and persistent wind events with seaward direction favorable for drift initiation in direction of ice edge. This observation is important and confirms cold air and associated ice strength play significant role in defining stability of immobile ice cover.

Figure 3 illustrates distribution of two-day average wind speed observed during destabilization events over cells in considered forecast zones by principal directions-TO sectors and sorted by scenarios of events based on the history of observations. Note the highest frequency of destabilization events in the offshore forecast zone is associated with N-NW sectors that can be explained with two reasons:

1. Fast ice boundary proximity along the north-eastern coastline that adds to stabilization of ice cover in the area versus higher degree of drift freedom towards more mobile ice cover in the West.
2. Prevailing Easterly winds over the region during winter.

Frequency of events with wind towards coastlines is significantly smaller and for stable ice cover break-up requires significantly higher 20-25 knots average wind speeds versus majority of events towards the west being with 15-20 knots range. Destabilization events associated with low wind speed below 15 knots occurred during thaw periods with weaker ice cover requiring lower threshold.

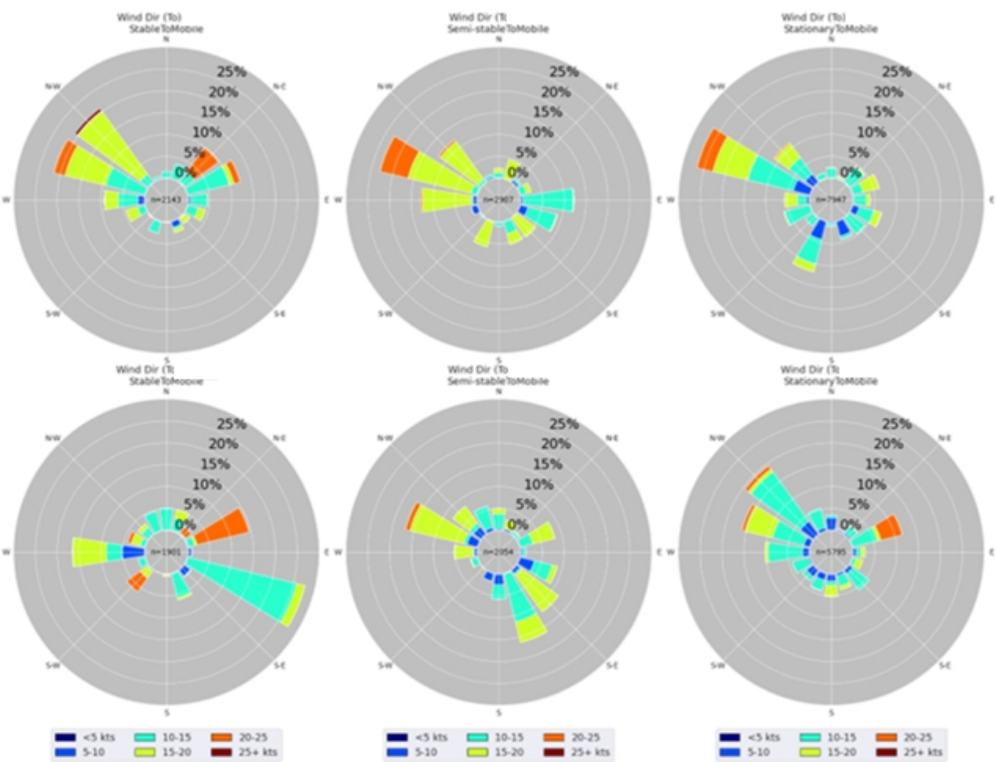

Figure 3 Distribution of two-day average wind speed observed during destabilization events by directions-TO in cells over offshore (top) and pre-coastal (bottom) forecast zones.

As for the pre-coastal zone three typical stable ice cover break-up scenarios can be distinguished:

1. Western direction with dominating portion of speed in range from 15 to 20 knots. Note lower speeds are possible.
2. ENE events occur despite obstruction in form of coastline, but wind speed needs to be in range from 20 to 25 knots.

3. Majority of destabilization events occur in ESE direction with two-day average wind speed in range 10-15 knots.

Semi-stable ice cover destabilization is normally associated with seaward drift events. WNW and NW wind prevails to destabilize stationary ice cover. Northerly and Southerly drift is constrained for all destabilization scenarios.

Figure 4 illustrates spatial distribution of events transitioning from immobile to mobile states with associated mean wind speed averaged for events as observed in each cell of the grid over the whole region. This infographic should be considered with due note of immobile ice cover distribution in the region. Thus, statistical description of events corresponding to stable ice cover is more relevant to the areas along the Northern and Eastern shores where frequency of this category occurrence is significant. Whereas semi-stable and stationary conditions were observed in the central basin of the region thus derived statistics of destabilization events in this area is based on more populous dataset. Practically, it means that grid cells with low count of events will normally have generally higher values of corresponding wind speed that is rather explained with averaging mechanism than with associated physics.

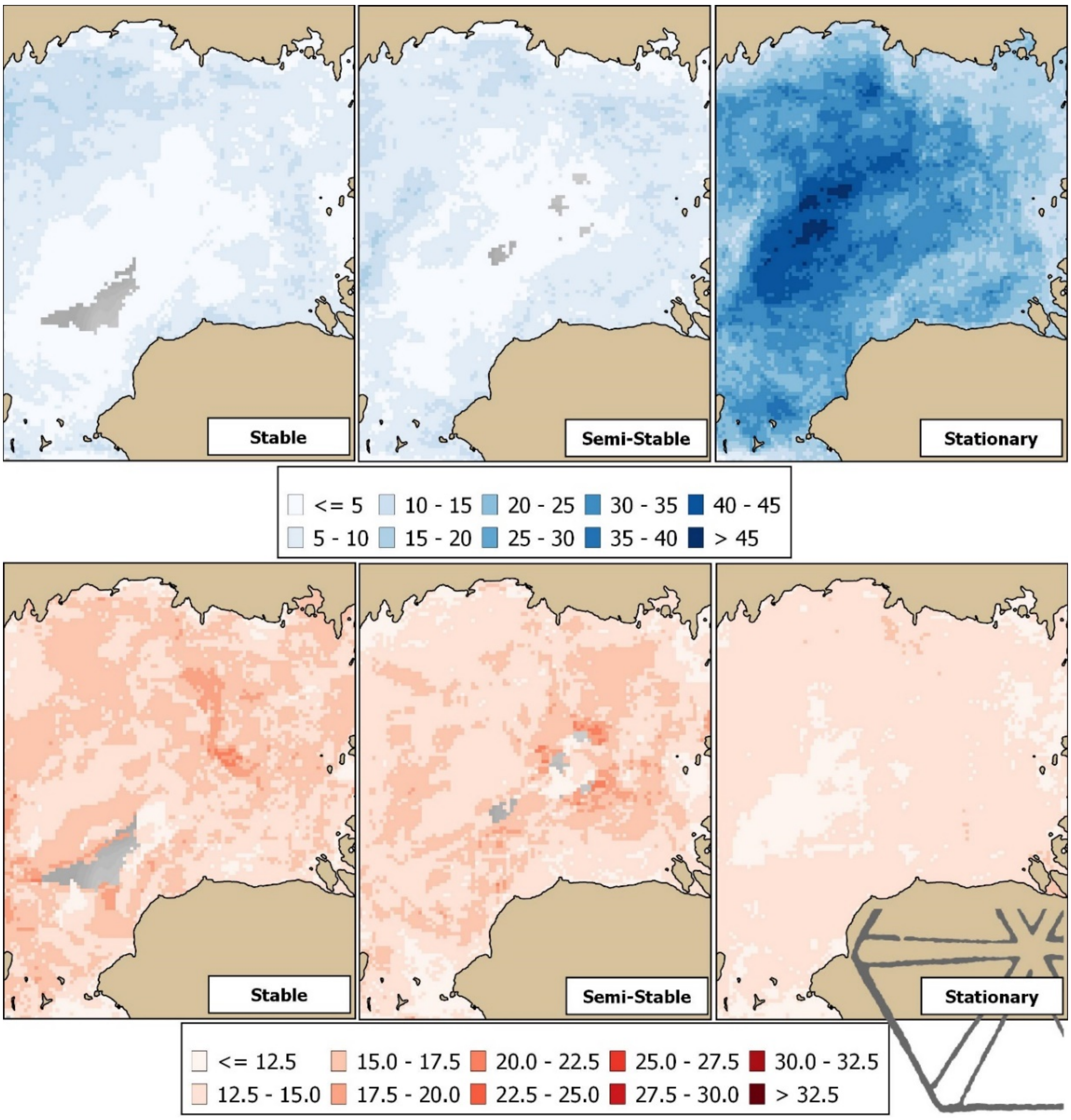

Figure 4 Spatial distribution of ice destabilization events count from immobile state (stable

(left), semi-stable (middle), stationary (right)) to mobile state (top). Average wind speed in knots for the events (bottom)

DISCUSSION

Derived correlations during the exploratory phase have shown two-days maximum wind speed parameter is indicative of driving force needed to trigger destabilization events depending on ice thickness and strength. The following figures summarize distributions of maximum wind speed observed during destabilization events versus weighted average with segmentation by relative ice strength. Maximum wind speed required to trigger destabilization events from stable and semi-stable state to mobile for ice thicknesses below 20 cm varies from 15 to 30 knots near coast. The range covers any significant force wind in the history of observations regardless of ice strength. Greater thicknesses require higher wind speed from 15 knots at 20-25 cm thickness and cold strong (relative ice strength more than 30%) ice up to 27 knots at 35-40 cm.

Figure 5 Two-days maximum wind speed observed during destabilization events at pre-coastal zone versus weighted average ice thickness in cm. Color of points indicates relative ice strength estimated during the events.

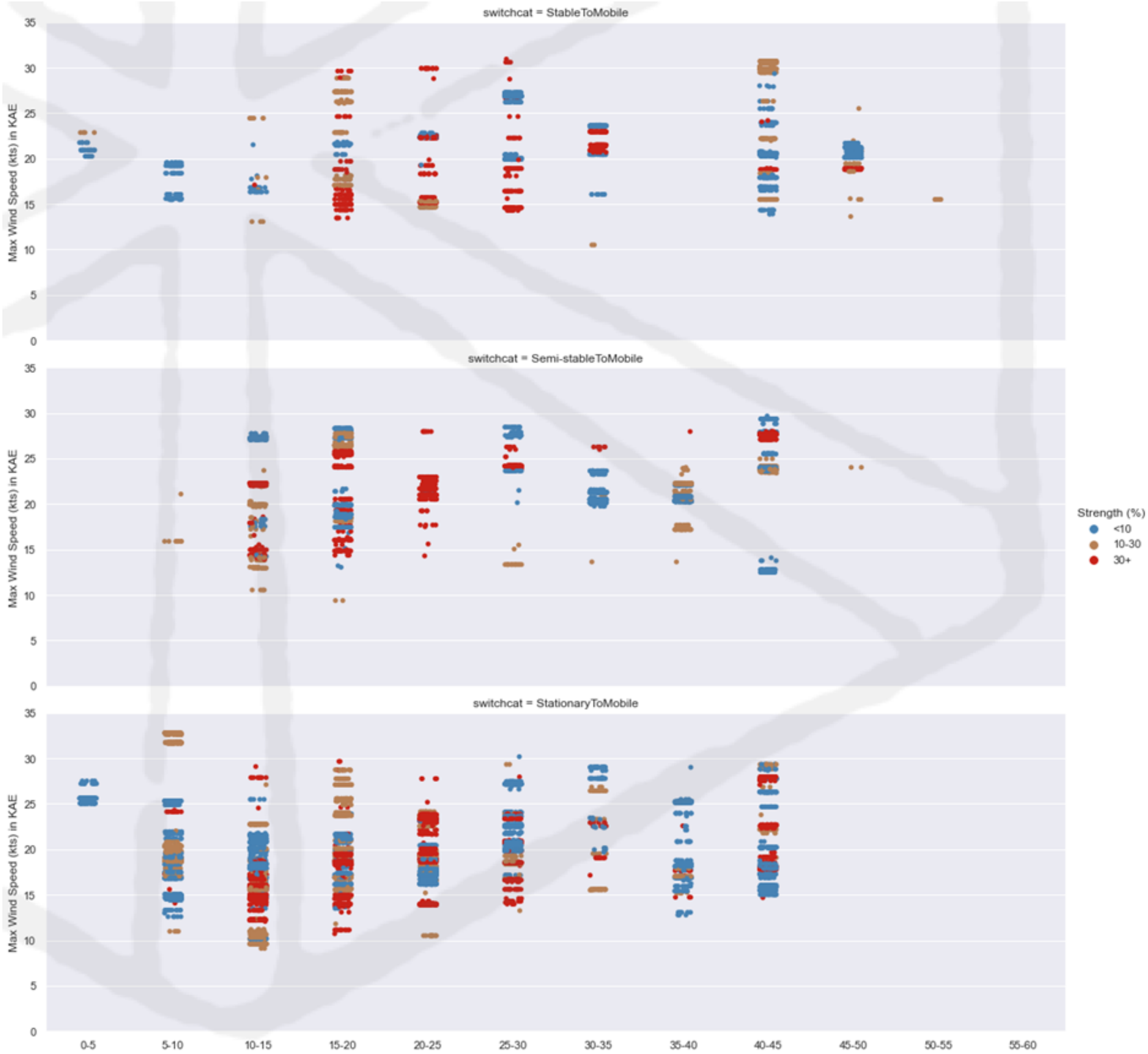

Figure 6 Two-days maximum wind speed observed during destabilization events at offshore zone versus weighted average ice thickness in cm. Color of points indicates relative ice strength estimated during the events.

Further classification by fetch length, bathymetry and frequency of obstacles narrows down the scatter of wind speed values. Linear regression model for each segmented set of conditions observed in the interpreted ice conditions becomes a powerful tool for regional scale forecast that picks hazardous combination of ice cover characteristics and wind speed from the forecast data. This approach forms the basis for commercially based ice hazard identification, arrival time estimate, and data driven alert system for specific operations and locations across the whole region.

CONCLUSIONS

This exploratory level research project of principles guiding ice cover response to weather conditions has demonstrated the key ice cover parameters that have controlling effect over response to wind action. Wind to drift correlation explaining transition of immobile ice cover to mobile state was presented in ranges and limits of acting force for combination of ice parameters. Illustrated dependencies and distributions describe ice cover destabilization events in the Caspian region that can be used for planning operations that are sensitive to ice drift effects and require operational planning of mitigation measures to reduce impact from moving ice cover.

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