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 Sea Ice Cover Hindcast Database

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

ABSTRACT

The Caspian Sea is a land locked water body in the central part of Eurasia. Its northern shallow part is seasonally ice covered. Intensive economic activity comprising oil and gas, fishery, and marine trade take place in this part of the sea. Some of them require assessment of impact from ice actions. ICEMAN.KZ developed the database with daily observations covering the whole region with ice cover characterization. More than 8000 SAR (Synthetic Aperture Radar) and optical images were processed for ice charting purposes to derive ice charts and analysis to feed the database that now contains data from 2005 to 2023. Internal ice monitoring program and database structure were developed to suit operational and engineering applications for offshore activities. WMO (World Meteorological Organization) standard ice characterization was enhanced with more parameters recorded daily for high precision insights. This paper describes the approach used to compile the dataset and discusses possible practical applications.

KEY WORDS: Caspian Sea; Ice database; Ice charting, regional ice monitoring.

NOMENCLATURE
ECMWF (European Centre for Medium-Range Weather Forecasts), ERA5 (latest climate reanalysis produced by ECMWF), KHM (KazHydroMet), METAR (Meteorological Aerodrome Report), RHM (RosHydroMet), SAR (Synthetic Aperture Radar), SoD (Stage of Development), WMO (World Meteorological Organization).

INTRODUCTION

The North Caspian Sea plays a significant role in the life of communities along the coast supporting economic development of post-soviet countries. The longest part of the coastline resides in the Kazakhstan sector of the sea where Oil & Gas is a traditional trade that has started in 1940s with onshore development. In 2000s industry moved offshore with start of Kashagan exploitation and more smaller fields either going through exploratory phase or pending investment as described in Skolsky et al. (2010). Being ultra-shallow and seasonally ice covered, the area is challenging for engineering offshore structures and planning marine operations as discussed by Verlaan and Croasdale (2011). Conditions require that custom built units (Arpiainen, et al., 1999) and specific approach to offshore structures design to account for ice issues (McKenna, et al., 2011) are used to maintain operations. The key design load considerations are based on ice related loads and interactions among others that guide development principles of fields' exploitation in the region.

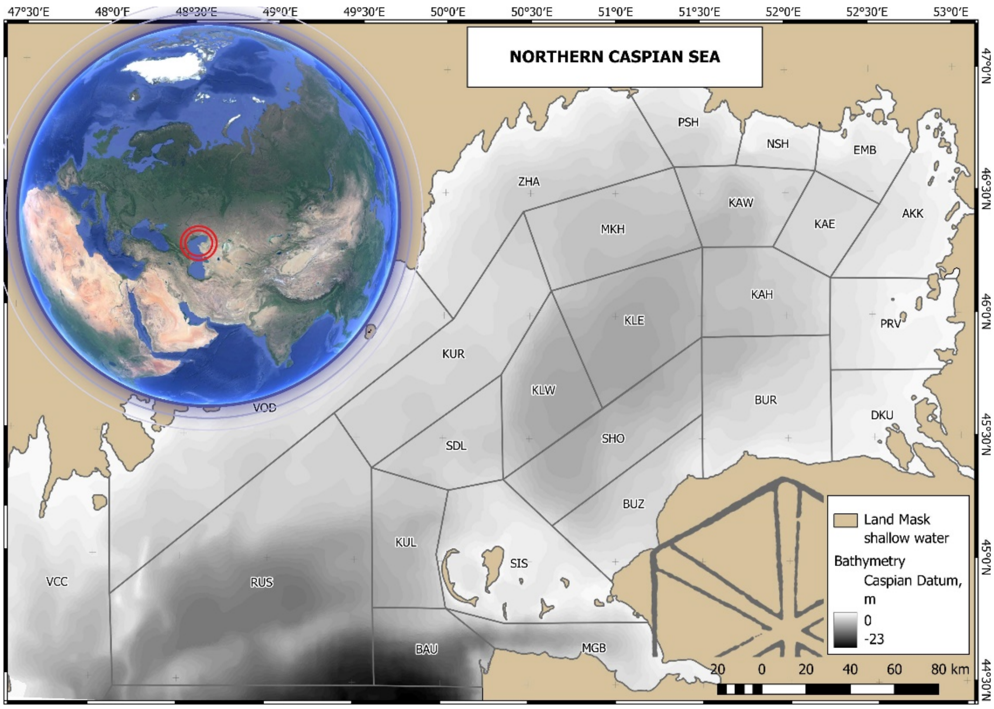

Figure 1. Northeast Caspian Sea.

Unlike the Arctic regions focusing on sea ice studies, the Sub-Arctic Caspian was not closely monitored during Soviet times and after the collapse of the Union. Russian institute of Arctic and Antarctic have collected weekly observations (AARI online), RosHydroMet and RosMorPort monitor Volga Caspian channel closely, but their data is classified and not distributed. Scientific Research Center of Space Hydrometeorology "Planeta" (Planeta) collects publicly available images with some automatic classification and publish static charts. All of them collect data following WMO standard (WMO 2004, WMO 2014). Recent and continuing international cooperation in Oil & Gas resulted in significant advance of ice data collection with commercial projects targeted to monitor and record ice and metocean conditions in the shallowest Northeastern part of the sea. Most effort was made to study ice conditions here during Kashagan phase I and II oil-field development in 2000s. Croasdale et al. (2004) and Nilsen et al. (2011) describe what ice data was collected for Kashagan Phase I and II field development and how they did it. Jordaan et al. (2011) discuss how this data was transferred into ice environment probabilistic models. These datasets and detailed results of studies are only available for corporate use. Considering the above there is not many datasets available publicly with tolerable precision for researchers and independent engineering contractors to conduct their projects supporting offshore engineering, marine operations analysis, or climate change impact assessments.

ICEMAN.KZ was partially and/or directly involved in some of the projects as a subcontractor or contractor with various clients. They have collected key requirements for data acquisition program to build a database designed to answer needs of operational forecast to support marine activities and to build engineering criteria for offshore design. These requirements have formed their approach to conduct retrospective fill of ice observations going back as far as 2000 into the past. While the main data structure is based on WMO (WMO 2004, WMO 2014) standard other observations were collected to ensure more accurate forecasting precision for the specific operations taking place in the area and to ease engineering. Thus, as an example, the stage of development was enhanced with ice thickness values. SoD precision of 15-30 cm following WMO was deemed insufficient to analyze performance of vessels that are more sensitive to thickness variation than in the Arctic. Added parameters of mobility were recorded to support ice events description and retrospective scenario-based analysis. All the observations were made to ensure the best knowledge on ice cover composition is captured for every day in the history of ice seasons from 2000 to now based on available remote sensing, weather and metocean observations.

The resulting hindcast database is partially available for public access with sufficient data revealed to help climate change impact analysis (ICEMAN.KZ). This ice cover characterization dataset, merged KazHydroMet (KHM), METAR, ERA-5 weather observations, ice drift dataset collected as described by Kadranov et al. (2017), stamukhi observations by Sigitov et al. (2019), deformed ice data discussed in Kadranov et al. (2023a) are an overwhelming and the most informative basis for variety of applications. This paper covers a general description of database, discussion on collected parameters and examples of applications where it was put to practice during the recent years.

GENERAL METHOD

Hindcast database is compiled from multiple consecutive daily records of ice conditions during each season. Being a combination of direct observations for a day, short-term hindcasts and modelled interpolations in reference to the date when observation is compiled, each record represents the best-known information in the area of interest for a day. The major purpose of compiling this dataset is having a regular and temporally coarse enough dataset to track changes resulting from corresponding metocean conditions. The dataset is also easily analyzable statistically because gaps in information both spatially (remote sensing data coverage) and temporally (cloudy days with no SAR data) were removed through infill and modelling performed during the ice analysis.

The process of hindcast database filling for a date follows the logic presented in Figure 2.

1. All remote sensing and metocean data are downloaded, processed, and stored for analysis.
2. Operator performs daily analysis based on all available data. After completion daily analysis is added to database.
3. Daily ice conditions data is further processed and aggregated depending on required statistical product and analysis.

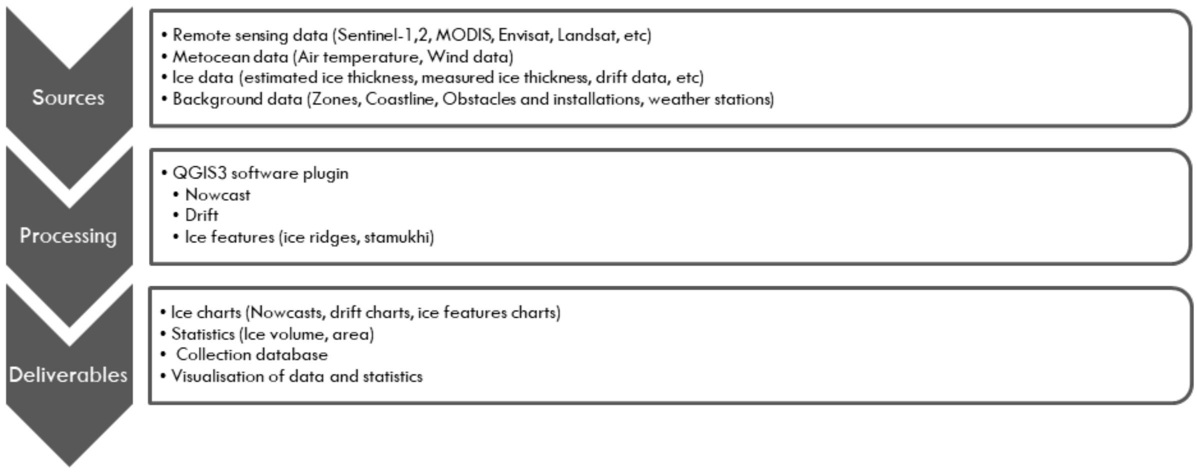

Figure 2. The workflow of Hindcast database creation.

DATA SOURCES

Multiple data sources contribute to daily analysis eased with complex data management system aggregating daily indices for each zone. The following subsections provide more detail on these sources and how provision flow was automated to efficiently deliver the most essential information to analysts.

Remote Sensing Data

More than 8000 SAR and optical images were processed for ice charting purposes to derive ice charts and analysis to feed the database. There are several optical platforms with MODIS being the main bus supplemented with higher resolution Landsat and Sentinel-2. ESA's SAR platforms provide higher accuracy and more reliable observations. Combination of all platforms form the basis for daily ice observations in the Caspian Sea.

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a satellite-based sensor used for earth and climate measurements. There are two MODIS sensors in Earth orbit: one on board the Terra (EOS AM) satellite, launched by NASA in 1999; and one on board the Aqua (EOS PM) satellite, launched in 2002. Interpretation of bands composition that provide RGB images was used for hindcast operations. Resolution of these images is about 250 m per pixel which is good enough to deliver general ice cover characterization and for change detection to find and confirm major events. Images are available twice a day with about 1-3 hours gap. Being an optical instrument, this platform has limited use during cloudy weather.

The Sentinel-1 mission includes a constellation of two polar-orbiting satellites, operating day and night performing C-band synthetic aperture radar imaging, enabling them to acquire imagery regardless of the weather. Images have been available since 2013. Their resolution is about 30m, but the areal coverage doesn't cover the whole North Caspian Sea area. The main disadvantage is revisit time of satellites which is approximately 1-3 times per week (when A and B were acquiring on every pass over the sea).

ERS and Envisat SAR images with lower than Sentinel-1 resolution and attendance were used for hindcast before 2013. Landsat series and Sentinel-2 optical images were mainly utilized for tracking local ice conditions and small-scale displacement, stamukhi observations where higher resolution is needed.

METAR, KazHydroMet and RosHydroMet weather stations

There are several ground stations which provide publicly available weather data. The location of stations is presented in Figure 3. METAR (NOAA, 2023), KazHydroMet (KazHydroMet, 2023) and RosHydroMet (ESIMO, 2022) stations both offshore and along coastline onshore deliver data at their location and with different frequency. These observations are harvested automatically as a separate entity for further use in a merged grid over the sea.

Long-term Historical Reanalysis data (ERA5)

ERA5 hourly surface air temperature and wind data on single levels from 1951 to present reanalysis dataset is used to aid daily nowcast production. ERA5 is the fifth generation ECMWF atmospheric reanalysis of the global climate. Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. ERA5 data is provided in gridded format with 0.25°x0.25° grid resolution for atmospheric parameters as illustrated with Figure 3. More information can be found on the official website (ERA5 online).

ECMWF forecasts (ECMWF, 2022) and their ERA5 reanalysis are known for reporting generally warmer air temperature in the Caspian region. ICEMAN.KZ rectifies ERA5 air temperature records introducing correction for error derived from difference of observed values at weather stations along the coastline and nearest grid points of ERA5. These corrections were introduced into the whole grid proportionally to the distance to weather stations. Resulting dataset has shown better correlation with observed results of air temperature changes. For example, relatively mild cold snaps resulting in ice cover formation would not be picked with original ERA5 grid values. Whereas modified grid predicted values of accumulated freezing degree days sufficient to initiate the first ice appearance. This method of air temperature data management was found to have sufficient precision for the purposes of ice related issues in forecasting ice events from the experience of operations. ERA5 wind data was found to provide good correlation with ground measurements and was not changed or corrected.

Background data

Background data including coastline for various annual sea levels, digital bathymetry model, forecast zones for aggregation of statistics, obstacles to free drift, artificial islands gave context to analysis of ice cover behavior on local scales.

Wind induced water level surges and per annual changes of water level result in significant variation of shoreline shape in the shallow waters of North Caspian Sea. This variation is pronounced along the Easternmost coast where seabed slope is gentle and in the Seal Islands area. Water level trends based on annual mean sea level in the period from 2000 to 2023 were used to differentiate shoreline through the seasons in the history of observations. Using correct coastline from season to season has led to more accurate records of ice coverage and the possibility to extract the factor of changing Caspian water level from the other factors that affect ice cover development through seasons.

Digital bathymetry model was derived from navigation charts and remote sensing data. The latter was most useful in the ultra-shallow areas along the coastline. Although the sea is shallow, seabed features were important to describe processes of grounded ice features formation.

The whole area of North Caspian Sea was segregated into forecast zones (PSH – Peshnoi, KAW – Kashagan West, KLE – Kalamkas East, VCC – Volga-Caspian Channel, and others as illustrated with figure below) to aggregate key ice and metocean parameters into trackable and comparable indexes. Zones were linearized with the following reasoning behind:

- Operational requirements by Oil & Gas license blocks, intensity of economic activities.
- Legal binding and environmental monitoring standards.
- Recurring ice conditions development patterns observed every season.
- Frequency of typical ice events and observations.
- Similar patterns of seasonal development characterize freeze-up and break-up processes.

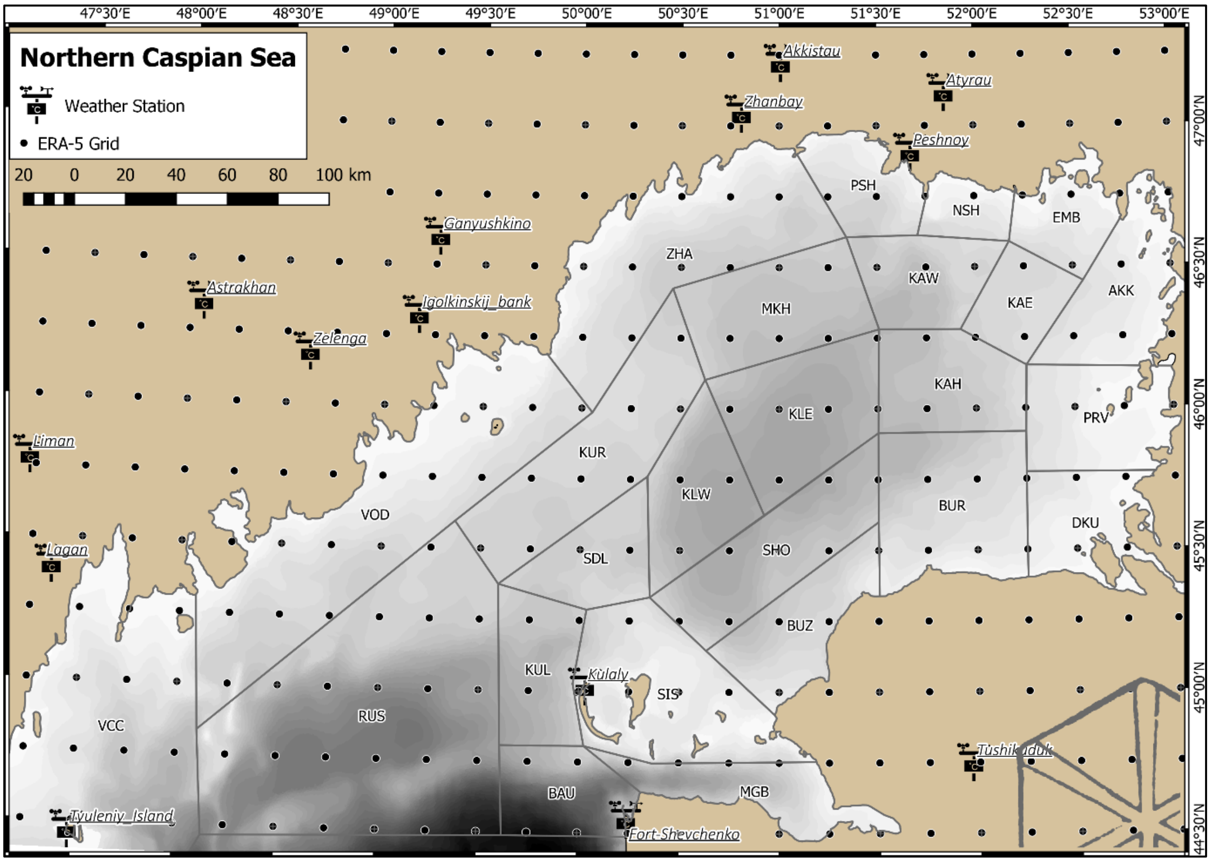

Figure 3. Location of METAR, KHM, RHM stations, ERA5 grid points and zones in North Caspian Sea.

Estimated Ice Thickness

The ice thickness component of the database is significant. It makes the dataset useful for a variety of applications from engineering to operational analysis. ICEMAN.KZ has derived an empirical ice growth thermal model for the region as described in Sigitov et al. (2023). Model estimates daily ice thickness change considering freezing and thawing rates due to air temperature and effects of solar radiation towards the end of winter. Refined ERA5 air temperature separately aggregated for each forecast zone is used for the calculation to receive more accurate hindcast values. Up to three values of ice thickness are calculated for each forecast zone individually starting with the first ice appearance in the zone and after each major ice event resulting in opening of vast areas and recurring freeze-ups forming consequent significant ice cover with second and third thickness. Tracking ice cover movement between zones, origin of ice formation and time spent in each zone with differing air temperature regime enables accurate estimate of ice thickness in mobile ice. Model's output is compared to physical observations in reference areas like Ural River, Peshnoi and Kulaly observations by KHM and port reports from Volga by RHM.

FRONTEND, PROCESSING ROUTINE, DATA STRUCTURE AND BACKEND

ICEMAN.KZ utilizes QGIS with data management plugin developed in-house specifically for the purpose of ice charting as a frontend for specialists producing daily analysis.

The analysis starts with upload of data of ice conditions for a previous day, the latest available satellite images, weather information and updated ice thicknesses estimated for forecast zones.

Small scale changes in ice edge or borders of homogeneous ice conditions are digitized manually with introduction of changes to earlier date analysis. For areas without remote sensing data coverage, area drift models are applied to find potential displacements and new shape of features observed previously. In the case of hindcast retrospective fill scope these modelled estimates are verified against the next day when such area is covered with an image. Each day analysis of ice conditions forms a set of GIS open format shape files for geography data with attributes of ice cover characterization (ice concentrations, mobility, ice thicknesses and floe sizes) coded according to SIGRID-3 format used for exchange of ice information (WMO, 2004). This ensures compatibility with other ice charting software packages. ICEMAN.KZ enhancements (mobility and ice thickness) are stored in added fields of polygons' attributes as shown in Table 1.

Operator relies on MANICE guidelines (Canadian Ice Service, 2005) by Canadian Ice Service to produce Ice Analysis in a standard and comparable manner. Plugin is equipped with means of aiding operator's manual work with preloaded estimates of ice cover parameters, visualization of detected changes, this day's and forecast weather for each zone, and progress tracking checklist. This aid ensures all required observations are verified and entered before submission of observation. Automation is achieved with preloaded data for analysis, automatically assessed fields like stage of development as per (WMO, 2014) assigned using recorded ice thickness and pre-built calculations.

Inbuilt quality check routines are applied with plugin automatically. These are both basic rules that, for example, ensure total concentrations always equal to the sum of partials in attributes of polygons and more sophisticated checks that ensure geographical data is consistent and there are no empty polygons or corrupt lines used to categorize ice cover. Depending on criticality, errors are corrected seamlessly or when human decision is needed prompts suggest fixing errors.

Table 1 Description of fields in the dataset.

Field Name	Description
polygon_id	Unique ID of polygon.
date_analysis	Date of analysis when ice cover observation was recorded
mobility	Each attribute recorded as mobility index is discussed below and summarized in
ct_perc	Total concentration of ice on the day of observation
ca_perc	Partial concentrations of ice in a polygon of homogeneous ice conditions as recorded on the day of observation sorted by ice thickness (A is the thickest)
cb_perc	
cc_perc	
sa_val	Ice thickness in a polygon of homogeneous ice conditions as recorded on the day of observation sorted by ice thickness (A is the thickest).
sb_val,	
sc_val	
fa	Floe size of ice in a polygon of homogeneous ice conditions as recorded on the day of observation sorted by ice thickness (A is the thickest)
fb	
fc	
sa	Corresponding ice stage of development depending on ice thickness values above. Fields are calculated automatically.
sb	
sc	

Ice thickness values in each polygon are entered by operators depending on estimated ice thickness values in each zone. The mobility attribute assigned to polygons of similar ice conditions is not a standard WMO parameter and is normally not regulated with any other external standards and procedures. However, this classification was found useful for ice hazard evaluations in support of marine operations and later to build ice-structures interaction scenarios for ice impact assessments for new developments of offshore infrastructure. Ice cover mobility attribute comprises several values which differ by degree of mobility: mobile, stationary, semi-stable, stable, compacting. A more detailed description of each mobility attribute is provided in Sigitov et al. (2023b).

After completion of day's analysis ice cover area, volume and daily change of the two values are automatically calculated recorded into the database along with other ice cover classification parameters. At this stage automated QA rules are applied stopping any further progress in case detected change is outside expected ranges. Examples of resulting one-day analysis with ice concentration, mobility and thickest ice thickness coloring schemes are presented in Figure 4.

Daily observations of ice cover classification in form of geographically referenced shapefiles are uploaded to PostgreSQL relational database designed for work with geographical data. Standard statistical aggregates are derived with more tables and scripts nested in the database. PowerBI report with ice cover related climate indices is an example of such aggregates that is free access to general usage. Database is compatible with and relates to variety of third-party software for data analysis and visualization. Depending on project and operational needs, data can be processed and exported in the required format. Spatial datasets are summarized into a common regular grid for further analysis.

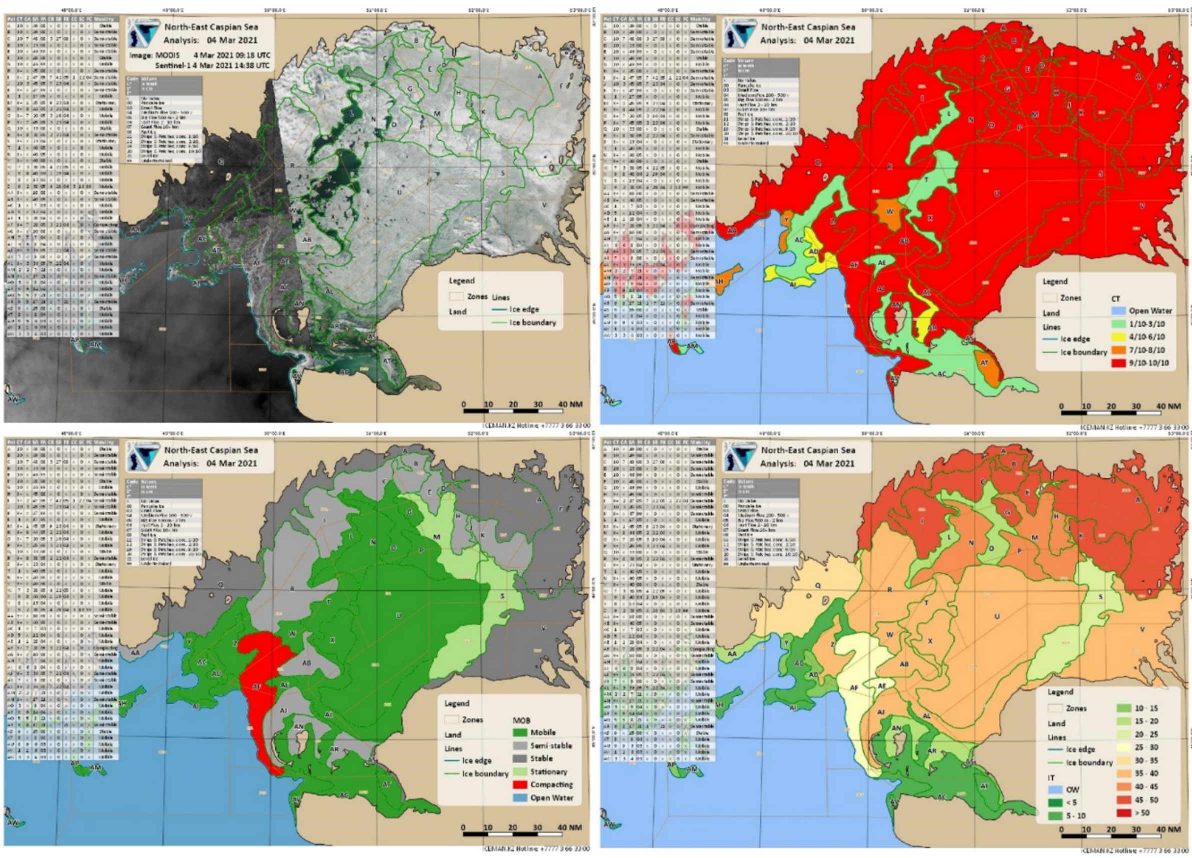

Figure 4. Daily nowcast analysis illustration the details of ice cover with transparent view (top-left), color schemed by total ice concentration (top-right), by mobility (bottom-left) and by thickest ice thickness (bottom-right).

DATABASE APPLICATIONS

Ice cover classification hindcast database has the collection of daily ice observations covering the whole area of the North Caspian Sea starting from 2005 to 2023 at the current date. The database enables a variety of temporal and spatial statistical analysis to answer the most demanding questions. Figure 5 shows only some examples of visualizations that are based on observations. Projects of the last years have shown structured approach to compiling the database was useful to deliver:

- Operational ice forecasts, defining ice freeze-up/break-up dates and progress of ice propagation or deterioration along marine routes. (Vernyayev et al., 2019b)
- Hazard from cross-drift analysis in channels through shallow waters as a more advanced case described by Bukharitsin et al., (2019). Introduced classification by seasons, ice cover mobility and features of this database have enhanced ice regime assessment for Marine access channel to Kashagan that was built recently. The key contribution of the assessment has changed the layout to decrease potential downtime due to hazard.
- Window of opportunity and persistence types of analysis for scenario-based ice hazard evaluation.
- Development of design criteria and probabilistic assessment of loads and structure-ice interactions in context of changing environment due to warmer climate and in case of the Caspian continuously falling water level. Such assessments require minimum input to only define the object for analysis and description of interaction scenarios using database parameters and other compatible data. Further query of the data finding coincidence of parameters identifies events that match scenario conditions based on observations. Impact on pipeline burial depth based on data regarding ice ridge density (Kadranov et al., 2023a) and stamukha density (Sigitov et al., 2019) can be an example of analysis based on many data sources merged into one analysis.
- Simulation of craft travel and travel time estimates for emergency response and operations based on known limiting conditions and performance records of crafts as discussed by Kadranov et al. (2023b).

More detailed examples and showcases of spatiotemporal statistical derivatives for variety of applications are presented in Sigitov et al. (2023a), Vernyayev et al. (2023), Sigitov et al. (2023b).

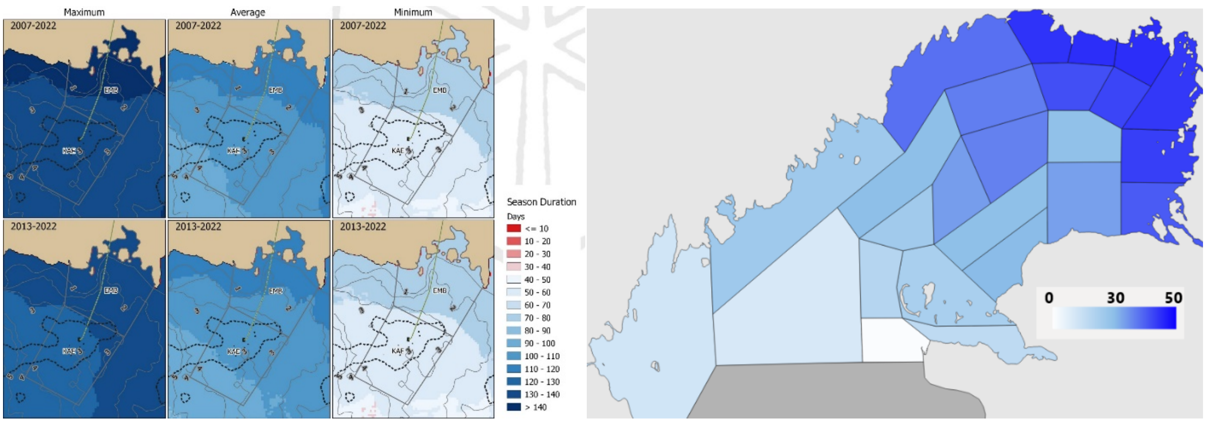

Figure 5. Examples of statistical products derived from Hindcast ice cover database.

CONCLUSIONS

ICEMAN.KZ developed the ice cover characterization database designed to support variety of applications Internal ice monitoring program and database structure were developed to suit operational, engineering and climate change analysis. General description of this database, its structure and sources of information, daily analysis routines and quality assurance were briefly introduced as applied to generate daily observations for the Northern Caspian region. This database contains the history of ice cover classification records from 2005 to 2023 with plans to extend it to 2000 and the future seasons.

The database was used extensively to deliver comprehensive, informative, and quantified insights to operations during the recent years mainly in the Caspian Sea to support offshore operations and design. Some examples were demonstrated and references to more detailed show cases were given.

This approach to characterize and structure ice and metocean data was used to deliver projects in the Arctic regions (Sea of Okhotsk, Kara Sea and Ob Estuary) as well. Experience showed that initial set-up of backend database and ice charting interface requires minimal adjustments for different geography. This involves introduction of new coastline and at some stage unique zoning based on acquired observations and project requirements.

Once the database and structure answer project requirements appropriate existing observations can be added with due consideration of observations frequency and tolerance to accuracy. If existing datasets are not acceptable to serve the purpose of a project or study these have to be generated given remote sensing data is available in the region of interest. Data availability to the date is mainly regulated with Sentinel-1 and Envisat coverage and frequency as free data controlling acquisition budgets. Commercially available SAR data may be useful to increase the period of hindcast or fill unacceptable gaps in data. As opposed to the Caspian MODIS and satellite platforms with optical instruments fade into the secondary remote sensing data source due to polar night.

ACKNOWLEDGEMENTS

This activity was only possible due to Copernicus project (https://www.copernicus.eu/en) as a part of EU space program which provides valuable publicly available data for our work such as images from Sentinel constellations and ERA5 climate weather data. The second but no less important contributor is NASA space program providing free access to MODIS and Landsat remote sensing data. Without such programs our work would not be possible, and their open data approach is highly valued in our group.

REFERENCES

AARI [online] Arctic and Antarctic Research Institute ice conditions dataset, available at: http://old.aari.ru/odata/_d0004.php [Accessed 01 March 2023].

Arpiainen M., Bäckström M., Juurmaa K., Wilkman G., & Veldman K., 1999. Development of the New Icebreaking Supply Vessel for Northern Caspian Sea. *Proceedings of the 15th International Conference on Port and Ocean Engineering under Arctic Conditions*, Espoo, Finland, POAC99.

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.

Canadian Ice Service [Online], 2005, Manual of Ice (MANICE), available at: https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manice-manual-of-ice.html [Accessed 01 March 2023]

Croasdale K. R., Comfort G., Crocker G., Metge M., Ritch R., 2004. A FIELD RESEARCH PROGRAMME TO ADDRESS ICE ENGINEERING ISSUES FOR THE NORTH CASPIAN SEA. *17th International Symposium on Ice*.

ECMWF [online] Weather Forecast dataset by European Centre for Medium-Range Weather Forecasts (ECMWF), available at: www.ecmwf.int [Accessed 15 December 2022]

ERA5 [online] ERA5 hourly data on single levels from 1940 to present, available at: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-evels?tab=overview [Accessed 01 March 2023]

ESIMO [online]. Data. Available at: http://esimo.ru/portal/ [Accessed June 2022].

Jordaan I., Stuckey P., Bruce J., Croasdale K., Verlaan P., 2011, Probabilistic Modelling of the Ice Environment in the Northeast Caspian Sea and Associated Structural Loads. *Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions*, July 10-14, 2011, Montréal, Canada, POAC11-133.

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

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 11-16, Busan, Korea, POAC17.

Kadranov Y., Vernyayev S., Sigitov A., 2023a. Caspian Deformed Ice Classification. *Proceedings of the 27th International Conference on Port and Ocean Engineering under Arctic Conditions*, June 12-16, Glasgow, UK, POAC2023.

Kadranov Y., Vernyayev S., Sigitov A., 2023b. Marine Units Performance Simulation under changing environment in the Caspian Sea. *Proceedings of the 27th International Conference on Port and Ocean Engineering under Arctic Conditions*. June 12-16, Glasgow, UK, POAC23.

KazHydroMet [online] Annual Caspian Hydrological Regime data from KazHydroMet, available at: https://www.kazhydromet.kz/ru/kaspiyskoe-more/ezhegodnye-dannye-o-rezhime-kaspiyskogo-morya [Accessed 10 January 2023]

McKenna R., Stuckey P., Fuglem M., Crocker G., McGonigal D., Croasdale K., Verlaan P., & Abuova A., 2011. Ice encroachment in the north Caspian sea. *Proceedings of the 21th International Conference on Port and Ocean Engineering under Arctic Conditions*, July, Montreal, Canada, POAC11-002.

Nilsen R., Verlaan P.A.J., 2011, The North Caspian Sea Ice Conditions and how Key Ice Data is Gathered. *Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions*, July 10 14, 2011, Montréal, Canada, POAC11 112.

NOAA [online] National Oceanic and Atmospheric Administration, National Weather Service Data portal, available at: https://tgftp.nws.noaa.gov/data/observations/metar/stations/ [Accessed 01 March 2023]

Planeta [online]. Available at: http://planeta.infospace.ru/planeta_products/archive/products [Accessed 01 March 2023].

Sigitov A., Kadranov Y., Vernyayev S., 2019, Analysis of Stamukhi Distribution in the Caspian Sea. *Proceedings of the 25th International Conference on Port and Ocean Engineering under Arctic Conditions*, June 9-13, Delft, The Netherlands, POAC19.

Sigitov A., Kadranov Y., Vernyayev S., Vernyayeva I., 2023a, Detailed Spatial Temporal Analysis of Caspian Sea Ice Thickness Distribution Based on Differentiated FDD. *Proceedings of the 27th International Conference on Port and Ocean Engineering under Arctic Conditions*, June 12-16, Glasgow, UK, POAC23.

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

Skolsky V., Skolskaya Y., Uvarov V., & Kambarbekov A. (2010). Ecological risk assessment of oil-gas fields development in Kazakhstani sector of the Caspian sea. *KazNU Newsletter*, Physical, Economical and Social Gepgraphy, 2(31).

Verlaan P., Croasdale K., 2011. Ice issues relating to the Kashagan phase 2 development; north Caspian Sea. *Proceedings of the 25th International Conference on Port and Ocean Engineering under Arctic Conditions*, July, Montreal, Canada, POAC11-171.

Vernyayev S., Kadranov Y., Sigitov A., 2019. Early Freeze-up Scenario in the Caspian Sea. *Proceedings of the 25th International Conference on Port and Ocean Engineering under Arctic Conditions*. June, Delft, POAC19.

Vernyayev S., Sigitov A., Kadranov Y., Vernyayeva I., 2023, Caspian Seasonal Ice Volume Trends in Recent History. *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.