P. Bukharitsin

STUDIES ICE CASPIAN, AZOV AND ARAL SEA

monograph

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P. Bukharitsin

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Каспийское, Азовское и Аральское моря относятся к мелководным южным замерзающим морям с сезонным ледяным покровом. В зависимости от суровости конкретных зим они ежегодно, полностью или частично, покрываются льдом. Каспийское море замерзает лишь в его мелководной северной части, в средней части моря лед появляется вдоль побережий только в наиболее холодные зимы. Исключительная мелководность этих морей, в сочетании с особенностями метеорологических и гидрологических процессов, создают условия для развития достаточно мощного ледяного покрова, представляющего серьезную опасность для морской деятельности. Многолетними исследованиями установлено, что на Северном Каспии, Азовском и Аральском море образование льда в прибрежной зоне происходит под воздействием одних и тех же факторов, что дало возможность прогнозировать характеристики ледового режима этих морей. Выполненные статистические расчеты основаны на материалах многолетних наблюдений и позволили получить общие зависимости, пригодные для практического применения. На их основе разработаны новые методы ледовых прогнозов. В условиях интенсивно нарастающей деятельности нефтяных компаний на Северном Каспии и Азовском море важность и значение ледовых исследований возрастает. К сожалению, после катастрофического падения уровня во второй половине XX века, Аральское море перестало существовать как самостоятельный морской водоем.

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In monograph known russian scientist, the researcher ice Caspian end Aral Sea epidemic deathes entered the reports, presented by author at period with 2000 on 2020 on international conference and symposium, denoted study sea and river Ice different region globe:

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Proceedings of the 16th International Conference on Port and Ocean Engineering under Arctic Conditions. August 12–17, 2001. Ottawa, Ontario, Canada (POAC'01);

Proceedings of the 21th International Conference on Port and Ocean Engineering under Arctic Conditions. July 10–14, 2011, Montreal, Canada (POAC'11);

Proceedings of the 22th International Conference on Port and Ocean Engineering under Arctic Conditions. June 9–13, 2013, Espoo, Finland (POAC'13);

Proceedings of the 22th International Symposium on Ice. Singapore, August 11 to 15, 2014 (IAHR'2014);

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Proceedings of the 25th International Conference on Port and Ocean Engineering under Arctic Conditions June 09–13, 2019, Delft, The Netherlands (POAC'19).

Also, the most significant publications are enclosed in monograph in leading scientific journal.

Monograph is calculated on broad circle scientist and specialist.

RESEARCH OF SEA ICE IN ORDER TO PROVIDE SAFETY OF OIL EXPLORATION ACTIVITTY ON THE SHELF OF THE NORTERN CASPIAN [1]

ABSTRACT

The Caspian belongs to the inner seas with seasonal ice covering. It is remarkable for its spatial and temporal heterogeneity and diversity in development of ice processes.

As a rule, every year ice covers only the shallow northern part of the Caspian. The duration of ice period depends on climatic and weather conditions in different sea ports and varies in warm winters from 20 days in the southwest to 110 days in the northeast and in cold winters – from 100 days to 170 days respectively.

Being a serious natural obstacle, the ice cover influences negatively on activity of marine sector of economy, which necessitates its thorough and comprehensive study.

INTRODUCTION

The Caspian Sea belongs to seas with seasonal ice covering and is marked for large diversity in ice processes. Being a serious natural obstacle at implementation of human economic activities at sea (fishery and seal capture, navigation and recently also at oil exploration works on the shelf of the Northern Caspian), ice cover limits significantly these kinds activity and creates a real danger to their safety. Exploratory works conducted recently by Russia and Kazakhstan in the shallow northern part of the Caspian Sea (including winter season as ice processes in the Northern Caspian).

Necessity and urgency of ice research is caused by the fact that the character and intensity of ice processes at sea had changed essentially due to the sea level rise happened in recent 20 years (since 1978) by 2,5 m approximately. Unfortunately, exactly in those years due to collapse of the USSR, the scientific programs, including those on ice research, were suspended and recently stopped at all.

In this work, data are used of expeditionary research conducted in February of 1996 and February–March of 1997 in joint Kazakh-American-Russian ice expeditions as well as maps of ice cover obtained by data of ice aerial surveys and at interpretation of television photos from the space satellite ISZ "Meteor". In this article, characteristics are given to hydro-meteorological and ice conditions in the Northern Caspian for the expedition period. The preliminary results of research of physical

[1] Research of the sea ice in order to provide safety of oil exploration activity on the shelf of the Northern Caspian / P.I. Buharicin, E.N. Labunskaya // Sixth international conference on ships and marine structures in cold regions ICETECH'2000 (12–14 September, 2000, St-Petersburg, Russia), 2000. – P. 552–555.

characteristics of ice cover and ice formations in shallow sea area at interaction of ice with vertical obstacle are published. Some data are given on winter algocenoses in sallow area of the southeastern Northern Caspian. Tentative data on species composition and biomass of under-ice phytoplankton, research of which was not practically conducted until recently [2].

Reconnaissance aeronautical research of area under exploration was carried out according to initiative of the State Company of Kazakhstan "Kazakhstankaspishelf" on the 22 February 1996 on plane "Hoker-125" owned by the airline "Petroleum Helicopters" (Figure 1). The result of implementation of ice aerial survey was that the state and characteristics of ice cover, location of collar and drift ice lines, places of grounded ice formations (huge hummock located on ground), ice holes behind collar ice, etc. were determined and charted. The area of future ice works was located.

Next winter of 1997, expeditionary works on ice were conducted during maximal development of ice cover in the Northern Caspian with the help of helicopter in area of former rochet testing ground located at sea to the north of the Burunchuk cape (the Buzachi peninsula).

According to the ISZ data, the most vinter expansion of ice cover in the Northern Caspian was on February 6 (Figure 2). The edge of drift ice laid from west to east at 5–10 m depth along the arch curved to the north from the Agrakhanski peninsula to the Bautino bey. Drift ice, mainly of grey-white and thin white ice, formed large and medium floes of compaction at the marc of 8–10.

Figure 1. "Hoker-125" owned by the airline "Petroleum Helicopters"

The line of collar ice was approximately along the 1-m isobaths in general direction from the southwest to northeast, and then turned round sharply to the south in direction to the Kulaly Island. Collar ice consisted mainly of thin white ice of 30–60 cm depth. The ice was even and lowly hummocked (prevailing hummocking at mark from 0 to 2), the highest hummocking was noted at the border of collar ice with drift ice and constituted 3–4 marks. In that zone large amount of small and medium grounded ice as well as linear formations were – multi-kilometer hummock ridges, cracks and ice-holes. Snow covering on grounded ice was everywhere not higher than 1 mark.

During researching of west and central parts of the Northern Caspian, intensive processes of thermal and mechanical destruction of ice went on. Reduction of drift ice compaction under the influenced of wind, formation of vast clear water area, as well as rapid and significant displacement of drift ice edge to the north were observed. Destruction of grounded ice in the Gurievskaya deep trench went on.

In area under research the state of ice changed insignificantly over that period. Only by the end of expedition some decrease of hummock and grounded ice height was noted by 1,0–1,5 m average against original caused by subsidence and compaction of forming floes due to the ice melting started and the first cracks in grounded ice appeared. Shearing of ice and hummocking were not observed.

The objects of research were old ships sunk on shoals, which earlier were used as targets for rockets.

The task of research was to assess the character and intensity of interaction of drift ice with stationary obstacle located vertically (in our case that was boards of half-sunken ships). Ships were at sea at depth of 5–6 m and in a distance of 10–50 km away from the coast (Figure 3).

Figure 2. Ice cover in the Northern Caspian on February 6, 1997

Figure 3. Ice studies on North Caspian

Episodic ice debacles and intensive drifting of ice caused by western and eastern storm winds prevailing at that time of the year were supplemented by surge fluctuations in period preceding expedition, assisted to hummocking processes. Solid ice fields had formed around sunken ships, and along shipboards there were giant multi-layer bulks of ice debris, the height of which constituted from 3–6 up to 15 m above the sea level, and their underwater foundation reached to the bottom. Some hummocks have a shape of multi-layer rings, which is explained by frequent changes of ice drifting direction. Such formations are called "ring stranded ice". At the lee face of stranded ice, as a rule, area of clear water is formed – ice-holes and canals [1] (Figure 4).

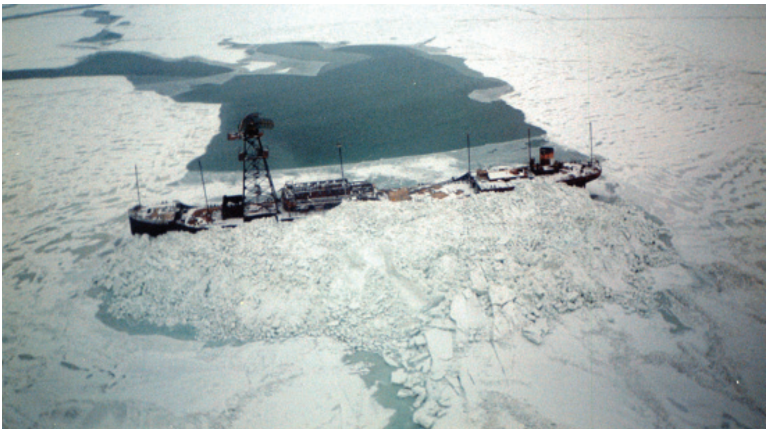

Figure 4. At the lee face of stranded ice, as a rule,
area of clear water is formed – ice-holes and canals

Ice formations around three ships were researched during expeditions.

Detailed geodesic survey of ice surface relief above the water abound ships under research was conducted with the help of electronic theodolite-tachometer. On chosen profiles laid radially through hummocks to the board of every ship the height of some hummocks and structure forming floes. The height of hummocks above the water and their underwater parts as well as sea depth were counted off from null surface that corresponded at that time to the level of Caspian Sea minus 26,7 m abs. and was measured with the help of satellite navigation system (GPS).

Measuring of size of floes formed stranded ice at the foundation, in the middle and on top as well as by layers allowed to reveal some regularity that is as follows. In primary period of stranded ice initiation, the first inner layers of stranded ice is formed of floes of small size and depth. As far as the sum of degree/days of frost is accumulated and related process of thermal growing of ice thickness goes on, during the next shearing of ice a regular layer is formed that exceeds the previous one by hummock height and floe size. Several layers of this kind could be formed in old stranded ice for a winter. Due to the fact that in such multi-layer hummock the ice debris could fill from surface down to bottom, in next shearing the ice field could not be cracked into small pieces but crawl over slowly coming off the water surface gradually and forming an ice mould. At further crawling of floe over inner layers of stranded ice, the mould becomes more and more steep and finally cracks. Huge floes stand almost vertically, sometimes overturn forming outer tremendous layer of stranded ice. The ice thickness of such floes constitutes 55–80 cm.

Within such ring stranded ice there is some volume of seawater that is fully or partially isolated from the other sea area during a winter period. Due to relatively small water volume inside the ice trap, lack of flowage as well as rather long period of isolation, within stranded ice conditions could appear favoring development of hypoxia in water and hydrosulfide pollution of ground.

Tens of wells were drilled using ice auger along the chosen profiles in every 3–5 m in order to determine thickness of ice layers and research relief of underwater part of hummock formations.

At the same time, samples of water, ice and soil were taken, and concurrent hydrological parameters were measured: temperature of water, air and ice (by layers), ets.

Temperature of water changed from −10–15 °C at the beginning of expedition to −2–7 °C in the following days. In this connection the range of temperature of ice by layers is also large: from −10 to 0,2 °C.

Temperature of water under the ice was everywhere within 0,0–1,0 °C.

Chlorinity of sea ice samples taken constituted 0,35 per mille average.

Samples of water and ice for phytoplankton were taken of 1-liter volume and fixed with 40 % formalin to 2 % of its density. At further laboratory processing samples of water were condensed through nuclear filter with pore diameter of 0,38 micron in funnel of direct filtration to the volume of 10 ml. Counting of cells was conducted in the Najjot camber.

Phytoplankton distribution in samples of water and ice taken for analysis in area of ice research was extremely uneven. Thus, at the point in latitude 45°41′ North and longitude 51°41′ East (sunk vessel conditionally named "Triple") at 3 m of sea depth and 2 m of ice layer thickness, 30 algae species and subspecies were determined. They were diatom – 27; cyanobacteria – 1 species. Total quantity of algae constituted 77,1 thousand cells/l, and biomass 0,050 mg/l. These indices are much lower then in summer-autumn period. Green algae *Binuclearia lauterbornii var. crassa,* Pt. Lavr. Et Makar / dominate by quantity (87 %) and diatom *Eunothia sp.* prevail by biomass.

At the second point at sea (under conditional name of "Derrick") in a distance of 16 km away from the first one, only 4 diatom species were noted in samples. Their quantity was did not exceed over 0,52 thousand cells/l, biomass – 0,004 mg/l. All species determined belong to haline forms.

In samples of soil taken at those points there was no hydrogen sulfide noted.

At the third point at sea of latitude 45°32′ North and longitude 51°27′ East, in inner isolated zone of ring stranded ice phytoplankton was not determined in water samples. It is interesting that exactly at that point of the sea samples of bottom soil were taken with strong smell of hydrogen sulfide.

CONCHLUSIONS

Shearing and drifting of ice in shallow Northern Caspian could influence significantly on human economic activity. Development of activity of the oil companies of Russia and Kazakhstan together with its foreign partners related to exploration of hydrocarbon resources on the shelf of the Northern Caspian required a significant scientific, ecological and technical support to this activity. Results of joint ice research, spelled out briefly in this report, were applied specifically in practice.

In 1999 in Astrakhan, the reconstruction of standard submersible drilling barge adapted specially for works under unique natural and geological conditions of the needs of Kazakhstan company OKIOC (Offshore Kazakhstan International Operating Company). Submersible barge platform and boards were modified in such a way that can withstand ice loads, which had been researched and analyzed during five years. Computer modeling was conducted as well. As a result, the barge area was increased twice and special ice bafflers were installed on both sides of the barge. The bafflers were designed to withstand the ice pressure. On the barge location place at sea the installation of a number of strong metal piles (with depth in the sea bottom down to 20 m) was designed on both sides of the barge to restrain the impact of drift ice and to make hummocking process on the distant approaches to the drilling platform more active. As a result, artificial grounded hummock forms around the platform and serves as a reliable protection against the ice.

Simultaneous biological research conducted during the ice expedition confirmed assumptions related to depressing impact of ice processes on conditions of formation and development of biocenosis.

Appearance of small-scale zones with hypoxia on the shallow areas with intensive hummocking and accumulation of grounded ice in winter was determined to be a well-spread phenomenon. It leads to sharp reduction of species composition and total biomass of phytoplankton in zones with hypoxia and in some cases to its full disappearance.

As sallow parts of the sea bottom constituting over 50 % of the Northern Caspian area (over 200 square kilometers) are subject to ice ploughing (interaction of drift ice with sea bottom), it could be stated that these processes have mass (although seasonal) character. Due to this fact, they play an important role in ecology of this water body. Along with purely mechanical motion of huge masses of bottom soil, the processes of depression of the bottom, island and coast vegetation and organisms happen as well. For instance, submarine research showed that the Caspian crayfish avoid building their holes on the sea bottom grounds subjected periodically to the ploughing influence of ice.

During the spring breaking, ice cover can also play a positive role of cleaning estuarial inlets of the Volga and Ural rivers and coastal sallow areas from the last year dead vegetation, thus decreasing possibility of hypoxia phenomenon there in warm season of the year.

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PHYSICAL-STATISTICAL METHODS OF ESTIMATION AND PROGNOSIS OF THE WINTER HYDROLOGICAL REGIME ELEMENTS IN THE NORTHERN CASPIAN SEA [2]

ABSTRACT

Processes of growth and hummocking of the Caspian ice have been used to develop empirical equations for predicting total ice thickness and degree of hummocking. Air temperature and wind are the primary inputs. Conditions of floating ice drift, processes of interaction of drifting ice, and systematic changes of ice edge are considered. The significant influence of sea level volume fluctuations on biannual changeability of hummocking processes, ice dynamics and winter hydrological processes in general are based on a large amount of observational data.

INTRODUCTION

I.A. Benashvili was the founder of marine hydrological and ice forecasting in the Caspian Sea. In 1937 for the first time he developed a method to forecast time of freeze-up. Y.A. Tutnev (1937, 1975), L.E. Veselova (1956), E.S. Karakash (1960, 1964), O.I. Sheremetovskaya (1976, 1978), A.I. Karakash (1965, 1969, 1988) et al made significant improvements to methods of short and long-term winter hydrological forecasts. Such attention to development of hydrological (ice) forecast is not accidental. It is explained by the complicated hydrological processes which are influenced by such factors as continental climate, exclusive shallowness of the northern part of the Caspian Sea, significant volumetric and deformational (surge) fluctuations of level, and specific wind regime. Until recent times, preference was for traditional methods of forecasting the main ice phases: date of freeze-up and break-up of the sea, ice thickness due to thermal growth. Later on there was a need to carry out different, non traditional forecasts: ice hummocking, thickness of ice rafting, ice dam depths and other winter hydrological (ice) characteristics and phenomena. Many of them were not investigated for the Caspian until recently. This paper will present methods of estimation created and tested by the author for forecasting these phenomena.

[2] Physical-Statistical Methods of Estimation and Prognosis of the Winter Hidrological Regime Elements in the Northern Caspian Sea / P.I. Buharicin // Proceedings, Volume 1. 16 International Conference on Port and Ocean Engineering under Arctic Conditions "Ice Engineering Applied to Offshore Regions" (August 12–17, 2001. Ottawa, Ontario, Canada), 2001. – P. 275-282.

SHORT-TERM FORECAST OF FREEZE-UP IN THE VOLGA-CASPIAN (ISSKUSTVENNYI) AND THE URAL-CASPIAN (PESHNOI) CHANNELS

Earlier, various authors carried out methods for developing short and long term forecasts of the main ice phases, ice at sea, and location of the ice edge. However, the hydrological and ice regime in navigation channels in the estuarial area of the Volga and Ural differ from the regime in the other shallow parts of the Northern Caspian Sea, and study of the ice regime in these channels received considerably less attention. Of the work devoted to ice processes in channels, the only one known is Ushakov, 1957. Unfortunately, that work was not completed. Until 1977, there were no acting methods to forecast freeze-up in navigation canal in the Northern Caspian. In the method under consideration the author used an empirical dependency of date of freeze-up on the date when average daily air temperature falls below 0 °C. The dependency had a correlation coefficient of 0,94–0,95.

The equation allowed forecast of the dates of the first and repeated freeze-up in the Volga-Caspian and Ural-Caspian navigation channels up to 3–6 days beforehand.

For the Ural-Caspian channel a chart was developed for the dependence of freeze-up at Peshnoi on actual temperature of water in the morning of the day of forecasting, value of air temperature decrease from the day of forecasting to the anticipated day of freeze-up and on the wind in the days preceding freeze-up. For the estimation formulas of expected dates of freeze-up, as well as for entering the chart, the one-day, three-day and ten-day weather forecasts are used for the appropriate areas of the Northern Caspian. Counting of the expected date is made from the earliest date of first observed freeze-up in channels – October 18. Average multi-annual justification of forecasts made according to this method on the Volga-Caspian canal constitutes 87 %, on the Ural-Caspian – 92 % (Bukharitsin, 1984).

METHOD OF SEASONAL FORECAST OF ICE HUMMOCKING IN THE NORTHERN CASPIAN

In 1984, one the first works was published devoted to the study of the ice processes in dependence on sea level fluctuations (Bukharitsin, 1984). The method considered here represents continuation of those investigations and is the first attempt to determine quantitative dependencies between ice hummocking of the Northern Caspian and the sea level. The objective of the research is elaboration of the method of seasonal forecast of ice hummocking in the Northern Caspian. For this purpose, the maximal seasonal values of forecasted element (hummocking) for individual areas and the entire sea area of the Northern Caspian was taken from maps of ice air surveys over the period from 1958 to 1983. Average annual values of the Caspian Sea level estimated by seven level posts over the same period were taken as a determining factor. Comparison of the average annual forecasted levels made in Hydrometeorological Center of the USSR with actual average annual levels of the Caspian over

15 years (1968–1983) proved the sufficient accuracy and reliability of these forecasts, and hence the possibility of their application in estimation of the maximal ice hummocking in the Northern Caspian. Primary data processing was made by methods of estimation of liner correlation.

Dependence correlation coefficients constitute 0,65 and 0,74. Probability of the method is 100 and 96 % respectively. The linkage of three variables (hummocking, level and wind velocity) was determined suitable for practical application in the entire Northern Caspian and individually for the seal hunting area. Expected ice hummocking is estimated according to appropriate formulas.

Considering the fact that the primary data used in forecasts are received in April-May, advance forecast of ice hummocking made by this method is 8–9 months. Admissible error of the method is ±1 mark of hummocking (assessment of sea ice hummocking according to the 6-mark scale of hummocking, from 0 to 5 marks, 1 mark is equivalent to 20 % areal coverage of hummocking)).

The limit of application of this method is determined by elevations of the Caspian Sea –27,5 to – 29,5 m abs. Above and below these elevations it is necessary to estimate the other coefficients for formulas. Accuracy of forecasts made by this method in 1982–1987 constituted about 100 % (Bukharitsin, 1988).

ESTIMATION AND FORECAST OF THE THICKNESS OF ICE LAYERS IN NAVIGATION AREAS OF THE NORTH-WESTERN PART OF THE CASPIAN SEA

As a rule, measuring of the sea ice thickness is made at the same permanent points located not far from hydro-meteorological stations. They should be located within coastal fast ice (still ice) and as possible in such places where no mechanic deformation occur. Thus, all data on ice thickness obtained as a result of multi-annual observations by the sea grid including the Caspian Sea represents information on ice thickness of natural (thermal) growth. Maximal natural ice growth in the Northern Caspian is observed in January-February and even in severe winters usually does not exceed 50–60 cm in the north-western part and 80–90 cm in the north-eastern part. However, these data do not always satisfy users. Experience shows that at sea ice occur more often as deposits, the total thickness of which significantly exceeds the ice thickness of natural growth.

Strong winds during period of ice cover formation facilitate breaking of fast ice, intensive shearing of ice and drifting of floating ice. At ice thickness from 1 to 30 cm rafting takes place.

The area of the Astrakhan sea road and sea area of the Volga-Caspian channel belong to the places of the most intensive shearing in the Northern Caspian. In mild and moderate winters the thickness of ice layers depends mainly on wind velocity. In severe winters the role of wind weakens due to strong fast ice.

Equation (1) was determined empirically by the author to allow estimation of thickness of the ice layers possible at a point in time in this area according to the measured ice thickness of natural growth and frequency of wind of velocity 8 m/s and more, noted in a preceeding period:

$$Hh = -0{,}7P + 6{,}2He - 21, \quad (1)$$

where Hh – thickness of ice deposit, cm;
P – frequency of wind of velocity 8 m/s and more for the period from the date of stable ice covering to date of estimation, %;
He – ice thickness of natural (thermal) growth for a day of estimation, cm.

From estimation of the thickness of ice deposit it is not difficult to proceed to its forecast. For that, we use the simple formula (4), connecting ice thickness of natural growth with sum of grade-day of frost (Valler, 1970). Advance forecast of ice thickness estimated by formula (4) constitutes from 3 to 30 days. Inserting then the obtained thickness of ice of natural growth and value of expected frequency of wind into formula (1) we obtain forecasted maximal thickness of ice deposit in a given sea area with respective advance time. Checking of estimation formulas by independent series justified the link reliance. Forecast errors did not exceed ±10 cm (Bukharitsin, 1986).

METHOD OF ESTIMATION AND FORECAST OF ICE DEPOSIT THICKNESS IN OPEN AREAS OF THE NORTHERN CASPIAN

There are scientific and practical interests in actual thickness of sea ice in open areas of the Northern Caspian. Unfortunately, until recently a method of forecasting was not available due to the lack of actual data. Archive data summarized by the author as well as on-line data from fishing vessels and seal hunting expeditions over the period from 1934 to 1989 allowed this gap to be filled in. Long experience of seal hunting expeditions on ice show that the ice cover in open areas of the Northern Caspian can multiply exceed the thickness of naturally grown ice due to rafting caused by strong winds and currents during formation of ice cover. In elaboration of this method the data were used on thickness of even ice and deposits obtained during sailing of ice-breakers "Ratmir" (1969), "Sergo Ordjonekidze" (1952), seal hunting expeditions on vessels "Galatika" (1970), "Tulen-1" and "Tulen-10" (1989), oceanographic expeditions of VNIRO on horses (1934), as well as on a basis of profile observations of Gidrometsluzhba (1950, 1951, 1954) and wind frequency according to the data of hydro-meteorological stations in the Northern Caspian: Kulaly, Tuleniy and Peshnoi for the same years.

Estimation of liner correlation of three variables was made by the author separately for severe and mild winters. At that it was determined that wind direction in that case is not important, therefore only data on wind velocity was used in estimations. The following coefficients were chosen for regression equations:

$$Hc = 4{,}6P + 11{,}1He - 213; \quad (2)$$

$$Hm = 0{,}7P + 1{,}4He - 18; \tag{3}$$

where Hc – thickness of ice deposit in severe (or extremely severe) winter, cm;
Hm – thickness of ice deposit in mild (or moderate) winter, cm;
P – frequency of wind of velocity 8 m/s and more from the date of steady ice formation to the date of making estimation (forecast), %;
He – thickness of level ice of natural (thermal) growth, cm.

Estimation of thickness of ice deposit for the current date is made through insertion of data on actual thickness of level ice of natural growth on a day of estimation and frequency of wind of 8 m/c and more for the period from the date of steady ice formation to the date of estimation (in %) into formulas (2) and (3). At that, all days are taken into account when at one or several hydro-meteorological stations in the Northern Caspian at least in one period of observations the wind velocity was noted to be equal or more than 8 m/c.

For estimation by equations (2) and (3) it is necessary to use already known empirical formula (4), connecting ice thickness of natural growth (He) with sum of freezing degree-days R (Bukharitsin, 1992):

$$He = 2\sqrt{R}. \tag{4}$$

SHORT TERM FORECAST OF LOCATION OF COMPACTING ICE IN THE NORTHERN CASPIAN

Ice drift is important in the formation of the ice cover in the Northern Caspian. In general, the character of drift is distinguished by complexity caused by shallowness, peculiarities of bottom relief, wind regime, influence of currents and sea level fluctuations.

In mild winters when fast ice covers only a small part of the coast of the Northern Caspian as well as in moderate and severe winters during autumn formation and spring break-up of the ice cover, ice drift follows the direction of the wind but with some deviations. Coefficient of ice drift (correlation of velocity of ice drift and wind velocity) on average is equal to 0,02–0,03. Coefficient of drift of free floating ice is usually more than that of compacting ice. For winds from a northern direction it is more (0,038–0,066) than for southern winds (0,032–0,042). In shallow sea areas many obstacles influence ice drift causing local compression of ice resulting in reduction of drift velocity. Angle of drift deviation from wind direction could have various values but more often it is 20o to the right. Sometimes there are cases of ice drifting against the wind (Veselova, 1956).

In moderate and especially severe winters, when most of the Northern Caspian is covered by fast ice and drifting ice lies as a narrow strip (of width 10–20 miles) along its border, drift of ice is mainly from east to west and south-west along the fast ice border and western coast of the Caspian. Velocity of the general drift of ice is about 7 km/day. The highest velocity is noted for winds from the north-west. At change of wind direction to the opposite one, velocity of drift declines and local zones and compression are formed. For north-west and south-east winds increase of ice compactness takes place in the drift zone.

In moderate and severe winters in the northern part of zone of drifting ice concentration in December constitutes 9–10 tenths, in southern part it does not exceed 3 tenths. In January-February concentration of 9–10 tenths prevails, in March it declines almost everywhere to 7–8 tenths. In area of the Astrakhan marine investigations, Chechen Island, on the contrary it increases to 9–10 tenths.

In mild winters the ice concentration rarely reaches 9–10 tenths and usually fluctuates from 1–3 to 6–7 tenths. Processes of spring break-up and clearing of ice from the Northern Caspian area proceed in a direction opposite to ice formation, i.e. from south to north. Time of start of ice break-up and intensity of this process depend on total amount of ice by the end of winter and combination of wind, waves, level fluctuations, currents, and temperature of water and air. In moderate winters approximately by the middle of March the open and shallow coastal sea parts to the north of 44–45° N latitude clear out. Most of the Volga estuary to the south-west from Ukatnyi island becomes free of ice by the end of March. In the first 10 days of April some aggregations of heavily hummocked ice survive only in the north-east.

In severe winters ice cover break-up proceeds slowly, with the time of fast ice break-up and clearing of western areas of the Northern Caspian shifting to the first half of April, and in eastern parts to the second half of April.

In mild winters the processes of ice cover break-up and clearing take place in time earlier than average.

Compacting ice (concentration of 7–10 tenths by 10-tenths scale) causes serious difficulties for winter navigation of vessels in the Northern Caspian. The ice cover is very dynamic and the location of the ice edge is rather changeable, spatially and timely. The main factors influencing on location of the ice edge are direction and velocity of wind and sea currents.

Research in the field of short term ice forecasting was started in the Caspian Sea at the beginning of the 1940s, as the necessity appeared to obtain data on expected shifts of the fast ice border and drifting ice edge which was of great importance both for operation of civil fleet and for the Navy (Benashvili, 1941). The work of N.I. Ivanov "Meteorological situation preceding ice freezing-over in the northern part of the Caspian Sea" (1941) was one of the first works. Unfortunately, that research was based on theoretical considerations only and was not proved by data of observations, therefore results obtained did not find practical application. N.V. Khatuntsev and M.M. Oganov (1943) made an attempt to develop a method of short term forecast of ice edge location, however that method either did not get a practical application.

Until recently, attempts to develop a method of short term forecast of ice edge location were not made, although the need for them has existed for a long time. Development of such method was impossible due to the lack of sufficient quantity data on the actual location of the ice edge. Data of ice surveys did not meet the requirements imposed due to their insufficient frequency. The possibility of obtaining suitable data appeared in 1978 in connection with regular observations of the state of the ice cover from satellite data.

To explain the method, first maps of ice aerial surveys and satellite data were used and analyzed for the period from 1979 to 1987. In total 254 ice maps were used, out of which 87 were maps of ice surveys and 167 were satellite maps. At the same time, all synoptic situations were analyzed to establish significant changes of ice edge location over the same period.

Prognostic dependencies were developed in the form $y = f(x)$, where x is the frequency of effective wind direction for a particular direction over a 10-day period; y is changes of edge location of compacting ice over that 10-day period, in minutes of latitude (1 minute = I nautical mile). Regression equation (5) and (6) were obtained empirically – for the northwestern part of the Caspian (from west coast to 50° E longitude):

$$y = 1{,}4x - 1{,}9, \tag{5}$$

and – for north-eastern part of the Caspian (east of 50° E longitude)

$$y = 2{,}1x + 1{,}3. \tag{6}$$

Correlation coefficient for these equations is 0,74–0,75. The method elaborated by the author in 1988 is successfully used in the current work. Its justification is not less than 80%.

Information on the state of ice cover in the shallow northern part of the Caspian Sea has increased recently. Since ice surveys have practically been stopped the application of this method and its further improvement is only possible thanks to use of satellite data.

The schemes of location of average multi-annual, minimal and maximal edges of compacting ice obtained by the author are used in scientific and operative-prognostic work. An ice atlas has been made (Bukharitsin, Vasyanin, Kalinichenko, 1992).

CONCLUSIONS

In this paper processes of growth and hummocking of the Caspian ice are studied in detail.

Conditions of floating ice drift, processes of interaction of drifting ice, and systematic changes of ice edge are considered. The significant influence of sea level volume fluctuations on biannual changeability of hummocking processes, ice dynamics and winter hydrological processes in general are based on a large amount of actual data.

Prognostic methods have been developed for estimation and forecast of ice hummocking.

Specialized forecasts of thickness of ice covers and location of drifting ice border have been successfully used for many years in the work of operational bodies of hydro-meteorological services of many marine sectors of economy and the Navy.

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ICE CONDITIONS IN THE LOWER REACHES OF THE VOLGA AND THE NORTH CASPIAN IN WINTER 2003/2004

According to current typification of winters by their harshness for the Lower Volga and the North Caspian, the last winter of 2003/2004 is characterized as "warm".

Table 1

Typification of winters by their harshness – the sum of degree/days of frost for the cold period (∑-daily average air *t* °C) for Astrakhan

Very Harsh Winter (VH)	Harsh Winter (H)	Mild Winter (M)	Soft winter (S)	Very Soft Winter (VS)
Over 900	900–700	700–400	400–100	Less than 100

The sum of temperatures below zero during winter 2003/2004 yrs. made up 55,7 °C at Astrakhan HM station, and 211,8 °C at Peshnoy station (in the south-east of the Caspian) – which as a whole is considered as "Soft" (S) winter for the North Caspian.

It should be noted that such a small sum of minimum temperatures was registered for the first time during the past 50 years at Astrakhan station, and a "very harsh" winter on the Northern Caspian was last observed in the season of 1968/1969 yrs. Thus, Very Harsh or even Harsh winters have not been observed for the last 35 years.

The pre-winter period was noted by rather high air temperatures on the Lower Volga and Northern Caspian. In late November the daily average t° in Astrakhan and the region was above zero (3,3 °C), while to the north of the region the frosts had already set up. As a result of unstable synoptic processes the ice formation on the Lower Volga and the North Caspian was occurring slowly and with complications that are characteristic of soft winters in conditions of regulated flow.

In fact, the fall-winter ice congestions on the Lower Volga in conditions of regulated flow can be observed to this or that degree every year. They result through considerable changes of the Volga ice-thermal regime, as well as the regime of water discharge and level variations that followed the construction of the Volzhskaia power station, the CPSU XXII Congress hydro-power station and formation of the Volgograd Water Reservoir.

The situation typical for "soft" winter occured due to the late and lengthy ice drift in the Lower Volga in January 2004. The ice jams formed on January 17–18th blocked the ship traffic on the Volga in the area of village Enotaevka (on riffles Selitreny, Shombaiskiy and Zamianovskiy). The increased water discharge of the Volgogradskaia power station produced intensive rise of the water level above the jams. In three days the water raised by 1,5 мeters. Under the pressure of water, the huge masses of ice started to driift down the river at the speed of 3,5 nodes (6–7 km/hr). Thanks to the ice-breaker "Kapitan Bukaev" the ships were rescued from ice captivity. However, in the night of January 19th on 20th the ships that had been moored to the piers of cargo area of Solianka and Astrakhan sea port were ripped off mooring by the drifting masses of ice. Again the icebreakerers came to rescue and prevented the helpless, ice-bound ships drifting with ice from bumping into the supports of the railway bridge across the Volga. However not everything went well. The pontoon bridge across the bayou of the river Achtuba which connected the village and the settlements of the Volga-Akhtuba flood plain with the left bank of the Volga was torn off by the ice shuga and carried far away down with the flow.

The sea ice processes were most intensive in the north-east of the Caspian in December. The appearance of steady ice was noted on December 1st-3d in the shallow coastal zone. By the end of the month the boundary of the fast ice ran at 2-metre depths and its thickness made up about 20 cm.

In the north-western part of the Caspian, by the information of hydrological station Lagan, the ice in the form of nilas appeared only on January 10, and persisted for 10 days. On January 20 the convoys began to put the vessels through by icebreaker down the Volgo-Caspian Channel (VCC) to the ice edge and back. During the whole month in the area of Isle Iskusstvenny in the VCC the ice situation was difficult for navigation – thick ice drift with the formation of extended jammed isthmuses.

Insignificant intensification of ice processes in the North Caspian and the Volga Delta took place in early January. In the Volga low reaches the first young coastal ice was noted in the first decade which by the terms was much later than the average long-term dates. By the temperature regime January was easier than normal, the slight frost persisted in the north-east which resulted in the ice edge gradually shifting south. The fast ice boundary ran at the depth of 2–3 metres. By the end of January, the compacted floating ice edge, by the AES info, shifted to the south and ran at five-metre depths. (Figure 1) The estimated thickness of ice made up 22 cm in the north-east part of the Caspian on January 23d, while in the north-west part the ice was in the form of nilas mostly 5–10 cm thick.

During the month of January, under the impact of frequent storm winds of variable directions and sea flows the floating ice edge was constantly changing its position. Intensive drifting, shearing and hammocking took place in the sea. Those were provoked by considerable surging fluctuations of the sea level, the range of which amounted to 1,5–2,0 m at the absence of restraining influence of the ice cover. Along the sea edge of the Volga delta, at the depth of 3–4 m, big stamukhas (the hummock formations set on the ground) were formed. (Figure 2)

The ice cover development achieved its seasonal maximum in the first decade of February. At this time the boundary of fast ice ran at the depth of 3–4 m while compacted floating ice edge at about 10 m isobath. The bulk of the grey-white and grey ice was located in the north-east part of the Caspean. In the west, along the coast the light and dark nilas of 6–8 points of concentration prevailed, and in the area of Isle Iskusstvenny – of 4–6 point, concentration. By the end of February, the thickness of ice in the north-east part of the Caspean made up 20–30 cm, and in the north-west – 5–10 cm.

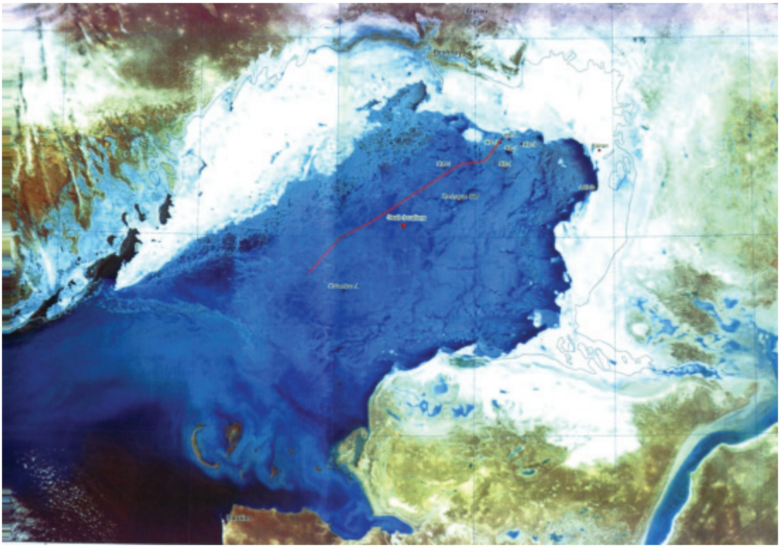

Figure 1. The ice situation on the North Caspian by the AES data as of January 30, 2004

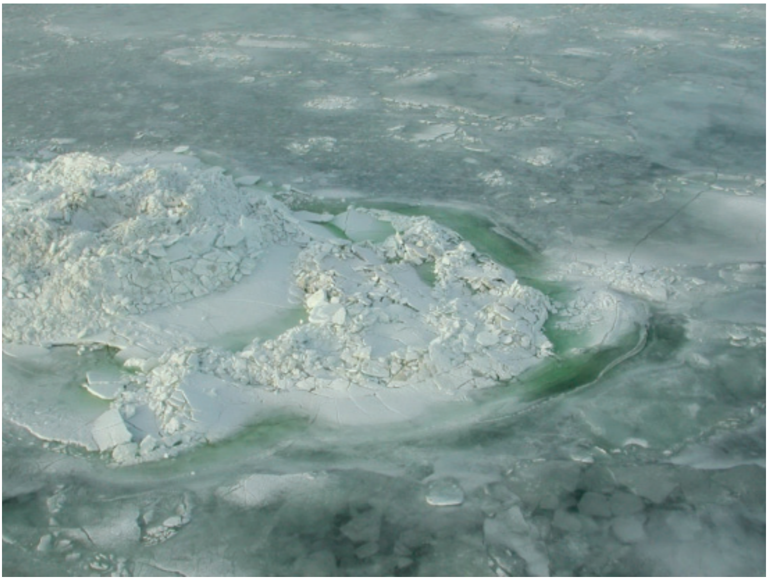

Figure 2. Stamukha on the North Caspian

During February a group of scientists from the Arctic and Antarctic Research Institute (St.-Petersburg) worked on the North Caspian. The objective of the research was stamukhas the formation of which is a real threat to the safety of the oil companies' activities in the shallow waters of the North Caspian. Every day a small group, with a lot of research equipment and instruments, were flown on the helicopter to the work area and landed on the ice. In the evening they were brought back on the helicopter (Figure 3).

Figure 3. Survey works on the Caspian ice

February and the first half of March saw multiple fracturing of fast ice, intensive drifting and hummocking of floating ice. From the second decade of February the thermal disintegration (thawing) of ice began. Floating ice of light and dark nilas in the north-west of the sea completely melted. Grey-and-white ice of the concentration of 7–8 points and fracturing of 1–2 points mainly preserved in the area of Gurievskaia borozdina. Fast ice remained along the north and north-east coast. Between the fast ice and floating ice there formed a vast flaw polynya the position and the size of which were quite variable depending on the wind velocity and direction.

In the second half of March there took place drifting of floe and its wreckage of the concentration of 6–10 points at the ice thickness up to 20 cm and distruction of 2–3 points.

Clearing of the sea from ice took place in the north-western part in the middle of March and in the north-eastern part in late March – early April (Table 2).

Table 2

The dates of the main ice phases at different observation points of the North Caspian

Location points	The latest dates of ice appearance	Dates of ice formation in winter 2003/2004	The long-term average dates of clearing from ice	Dates of clearing from ice in winter 2003/2004
Astrakhan	18,01	09,01	22,03	05,03
Isle Iskusstvenny	18,12	03,02	21,03	25,03
Lagan	n/a	10,01	n/a	20,01
Isle Clear Banka.	20,12	10,01	n/a	n/a
Seal Isle (Tiuleniy)	3,01	*abs.*	17,03	*abs.*
Isle Kulaly	29,01	03,02	17,03	20,03
Atyrau	18,12	03,12	02,04	n/a
Isle Peshnoy	16,12	01,12	01,04	02,04

Notes: n/a – information not available; *abs.*– none.

CONCLUSIONS

Thus, the winter of 2003/2004 on the North Caspian by the nature of the ongoing ice processes on the whole can be referred to warm or "soft" winters. At a closer consideration two areas can be singled out: the north-western part where the ice processes were weak and did not last long and the north-eastern part – in this region of the sea the ice processes ran in a more intensive way but to a lesser extent than during "mild" winters.

THE RESULTS OF THE INVESTIGATION OF DYNAMIC PROCESSES IN THE ICE COVER OF THE NORTH CASPIAN BY THE LONG-TERM DATA OF ICE AVIA SURVEYS AND AES PICTURES

The dynamic deformations of ice cover result from the fast ice integrity violation which brings to the fast ice fracturing (in different stages of its development) and the consequent redistribution of the floating ice under the impact of wind, currents, rough sea and fluctuations of the sea level. Wind is of critical importance in the ice cover dynamic deformations in the North Caspian. That is why the wind-driven drifting of ice intensified by the currents dominates in separate parts of the sea. The direction of the general drift is relatively stable in different winters. What really changes is the southern boundary of the floating ice which shifts to the south in harsh winters and to the north in warm winters. Shown below are the diagrams of general ice drift typical patterns [1] (Figure 1).

a b

Figure 1. Typical patterns of general ice drift:
a – at the south-east wind field; b – at the north-west wind field

In particular, hydrometeorological conditions the overall picture of the drift becomes more complicated through the i nstability of the speed and direction of wind and currents. The drifting ice carries away with it the surface water layers and gives rise to the under-ice flows that change the speed of drifting. The wind surge that creates the slope of the sea level which in its turn generates compensational flows distorting the drift – als, tells on the ice motion.

To obtain a detailed picture of the ice cover dynamics in winters different by the degree of harshness as well as that of particular areas of the North Caspian that are at a distance from the monitoring stations we processed the maps of the AES photo archives and, partly, the ice avia surveys materials [2].

To make electronic maps the ArcWiew GIS has been used which provides a ready tool kit. All spatial / dimensional data have the format of shape-file *ArcWiew* and extention *.shp*. For drawing a map, the shape-files of the programme itself are used as well as the newly built ones and the data from the tables in the format *dBASE*. The Caspian Sea level corresponds to benchmark –27,00 m.

The analysis of the AES photos made in the periods of the presence of ice cover makes it possible to define the direction and the speed of the general drift. The analysis is done by the location change of the patches of the drifting ice edges.

The materials of space photography were collated with the avia-surveys data on the closest dates. Bringing to a single scale and the transformation of images and avia surveys schemes were done by the outlines of the sea contours and specially selected noticeable reference points.

Below is an instance of the thematically processed data of the ice avia survey of the North Caspian as of January 30, 1984 (Figure 2) and AES picture obtained on February 3, 1984 (Figure 3).

The comparison of these two photographs obtained at an interval of 4 days shows that the identified sections of drifting ice boundaries (they are marked by a solid line on the diagrams) have shifted to a considerable distance.

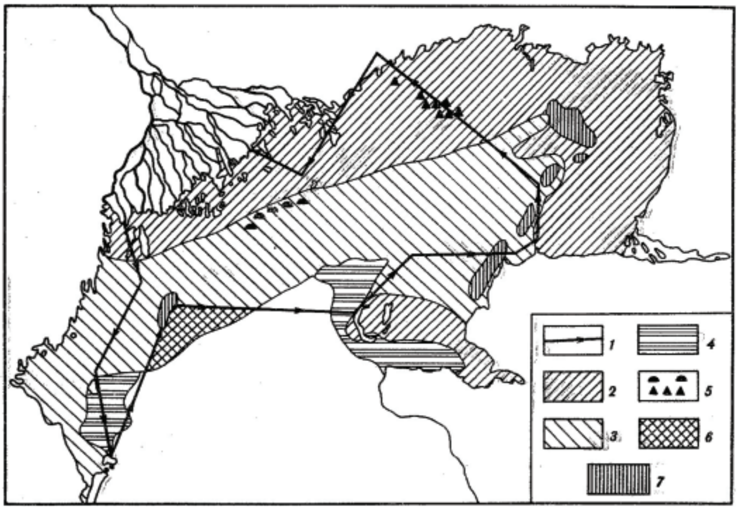

Figure 2. The ice condition status as of January 30, 1984 by the avia survey data

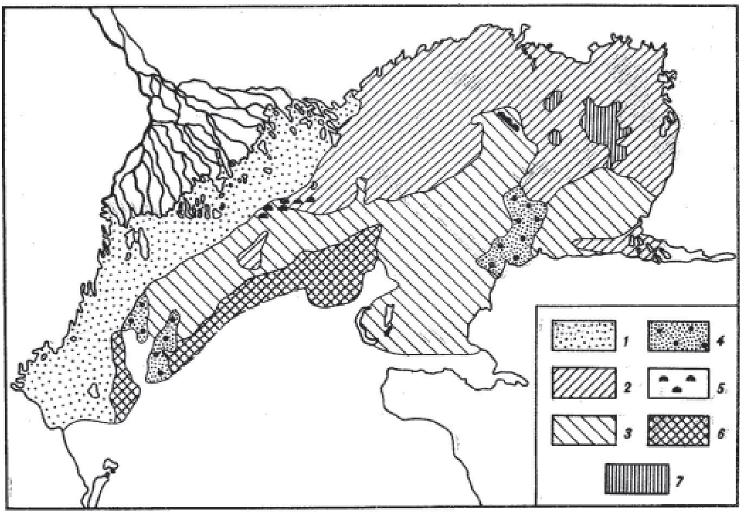

Figure 3. The ice condition status as of February 3, 1984 by the AES data

As it is evident from the comparison of the two diagrams, the configuration of the coastal line and the bench mark sections is identical. According to the data of the ice condition avia survey, the status of the ice as of January 30, 1984 was as follows:

The fast ice boundary ran along the coordinates of 45°25′ N latitude 47°30′ E longitude, 46° N latitude 51°25′ E longitude; 51°50′ to the west of the meridian 49° the fast ice consists of dark and light nilas, to the east of 49° it consists of grey ice. The degree of the fast ice melting makes up 1 point, and that of hummocking — 0–2 points. The coordinates of floating ice are as follows: 44°; 47°40′–44°30′; 47°50′–45°13′; 49°45′–44°53′; 50°10′. The floating ice is in the form of floe, floe fractures of dark and light nilas, ice cake at edges. Everywhere inclusions of floe and fractures of grey ice can be observed, with concentration of 7–10 points, hummocking of 1–2 points. In the south-east of Guriev borozdina there are a great number of fracture zones, on the banks there occur stamukhas, with ridges on the boundary between fast ice and floating ice. In the bayou Bakhtemir there is a freeze up with polynias, in the bends there are ice isthmuses.

The analysis of the materials of the ice surveys and telephotos from the AES allows to distinguish, depending on the brightness of the TV photos, five types of ice.

1. *Fast ice* (припай) — the picture is monotonous and indiscrete, no structure can be seen, light tone can be well distinguished in the whole spectral zone. In Picture 2 fast ice occupies the area adjacent to the coast between the deltas of the Volga and the river Ural and the region to the east of the delta of the river Ural.

2. Floating ice in the form of light and dark nilas in the form of floe and its fractures in the form of light and dark nilas, with concentration of 7–8 points — the picture is a little darker than fast ice and is permeated with streaks of darker colour. Everywhere there are grey inclusions of floe and its fractures. The degree of hummocking is 1–2 points. Fragmentation of ice is better seen within the range of 0,7–1,1 mkm.

3. Broken floating ice is best seen within the range of 0,5–0,6 mkm and is hardly seen being in the form of light veiling within the range of 0,7–1,1 mkm мкм. On the avia observation diagram the broken ice is not noticible at all in spite of the fact that the route of the flight ran across that region.

4. Brash ice floating under water resembles river shuga (it might be bottom ice coming up onto the surface), and is seen only within the range of 0,5–0,6 mkm.

5. On the photos the hummocks and stamukhas are seen as small dazzling white spots that are very well seen within the range of 0,7–1,1 mkm. The areas of their distribution are ascribed to the north up the river Volga on the boundary of fast ice and the main massif of ice. Another ridge of hummocks is located between the deltas of the Volga and the Urals parallel the coastline at the eastern edge of the Volga delta. A third ridge of hummocks can be seen along the northern and eastern boundaries of the Ural borozdina. On the avia survey diagrams the hummocks and stamukhas were not observed in this area either.

CONCLUSIONS

1. Mapping of the position of ice edge by means of AES telephotos of "Meteor-30" type gives more accurate results than the avia surveys since with the latter the accurate binding cannot be done and critical mistakes are possible when dealing with different types of ice of complex configuration.

2. Deciphering of the ice cover by aerospace data makes it possible to zone the ice cover on vast territories and single out up to five of its varieties. By the data from AES telephotos of "Meteor" type it is easy to trace and map thawed patches on ice, cracks and polynias; by the image tone there can be defined fast ice, floating ice of different concentration in the form of floe, its fractures, brash ice, hummocks, stamukhas, etc.

3. The watershed boundaries, like water-and-ice and ice-land (not covered with snow), are better tracked within the range of 0,7–1,1 mkm.

4. The television shooting from the satellites of "Meteor" type makes it possible to get an idea of dynamics, position and status of ice for the previous period since the ice, possessing certain inertia, serves an indicator of the previous meteorological situation (winds, snowfalls, etc.) which cannot be discovered in the materials of avia surveys.

For a more detailed grafic presentation of information on ice the format JPEG with 24-colour scale has been applied.

For each particular case of ice shooting the two graphic files are created:

– the AES images processed by theme;

– the map of the distribution of ice complete with the data on ice age, its thickness, concentration, as well as meteorological characteristics obtained by means of subsatellite observations;

– the creation of an electronic bank of satellite information makes it possible to solve problems of defining typical situations of speed and directions of the ice drift, the processes of ice compression and decompression, formation of fast ice polynias, etc. practically in every point of the sea basin at different wind fields.

– During the first observation period from 1978 through 2006 we processed and recorded on magnetic carriers about 400 ice maps in graphic and digital form. Such presentation of the information allows to directly calculate dynamic characteristics of the ice cover on a certain date in a particular area of the sea basin and obtain statistically significant values of the ice regime characteristics for practictical purposes.

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HYDRO-METEOROLOGICAL SUPPORT FOR PROSPECTING ON THE NORTH CASPIAN SHELF DURING WINTER PERIOD[3]

ABSTRACT

The Caspian Sea regime is characterized by the great space-and-time heterogeneity of its parameters through its significant length (1200 km.) Another specific feature of the Caspian Sea is the presence of ice cover. The Caspian belongs to the type of seas with seasonal ice cover.

INTRODUCTION

Normally, the ice covers shallow waters of the northern part of the sea. The duration of the ice period depends on how severe the winter is and it may last for 20 days in the south-west up to 110 days in the north-east; during mild winters it may last for 60–140 days, and in harsh winters – from 100 to 170 days. The presence of ice cover on the sea makes a great impact on the nature and intensity of hydrometeorological processes. Being a serious obstacle, the Caspian ice considerably impairs the research works on investigating the peculiarities of the winter hydrometeorological processes. For this reason the hydrometeorological processes on the North Caspian have not been investigated as extensively as those during the navigation period.

There exists a paradoxical situation: the average yearly parameters of a lot of components of the hydrological regime of the North Caspian, like rough sea, flows, salinity etc., are estimated only for the period of navigation, i.e. from April through October-November. Four or five winter months just fall out of estimation because of the unavailability of data, though it is just in this period that the great changes of those characteristics take place. In addition, the ice itself under the impact of wind, flows, rough sea, and the fluctuation of the sea level is in a constant and complex motion. The ice cover drifts, breaks into big pieces or gets consolidated.

In addition to purely scientific interest, the research into the hydrometeorological processes in the Northern Caspiy during the winter season is of great

[3] Гидрометеорологическое обеспечение поисковых работ на шельфе Северного Каспия в зимний период // П.И. Бухарицин, Б.Ю. Болдырев, Ю.В. Дозорцева // ББК 95:2. Г35. Материалы VIII Международной научно-практической конференции. Научно-технический журнал Геология, география и глобальная энергия № 3(34), 2009. Издательский дом "Астраханский университет", 2009. – С. 90-92.

practical value. At present the Caspian Sea has become a zone of mutual interests for the Caspian Sea states – Russia, Kazahstan, Azerbaidjan, Turkmenistan and Iran. The intensified shipping over the sea has made the issue of the necessity of the year-round shipping in the area of Astrakhan – North Caspian quite urgent. At present, an intensive prospecting and developing of oil-and-gas deposits is being done not only on the coast but in the basin of the North Caspian. Realization of these like many other important and potentially hazardous environmental projects is going to become impossible without the timely providing of the organizations which carry on such activities, with trustful hydrometeorological information, including the winter (ice) period.

At present the oil and gas production companies are able to obtain the forecasts on the sea level fluctuations, hazardous hydrometeorological processes and phenomena, and – which is most important – specialized ice condition forecasts.

The hydrometeorological service of the Caspian Flotilla has up-to-date equipment and highly professional personnel. Over the years the geoinformation system (GIS) has been used for both obtaining and analysing as well as processing meteorological data and the data on the ice cover condition from the artificial Earth satellites (AES).

The AES materials are successfully applied at the everyday mapping of actual ice condition and forecasting the ice situation for the nearest future.

For instance, in spite of the fact that in 2003 the winter was rather mild, there occurred real danger for the drilling platform "ASTRA". The edge of the drifting ice floe approached at the distance of 12 miles from the platform (Figure 1). The situation became a real threat to the platform since in the open sea when the winds are strong there often occur intensive ice drifting, shifting and hummocking while the drilling platform "ASTRA" has not got the appropriate ice protection. To lessen the risk, one of the Caspian Flotilla support vessels patrolled in the location of the platform with the purpose of constant monitoring the drifting ice floe edge progress.

In addition, the Caspian Flotilla Service regularly supplied the information on actual status of the edges of fast ice and drifting ice obtained by analyzing the satellite photos. The materials were provided for use to the consumers of hydrometeorological information in the form of specialized hydrometeorological bulletin which, alongside operational information, contained ice condition forecasts for the area of the North Caspian, the low reaches of the Volga, and the Volgo-Caspian channel. During the entire winter season of 2002/2003 yrs. the daily, three-day, weekly and monthly meteorological forecasts were constantly transmitted.

nique and predicting the components of the hydrometeorological regime hazardous for marine economy and activities.

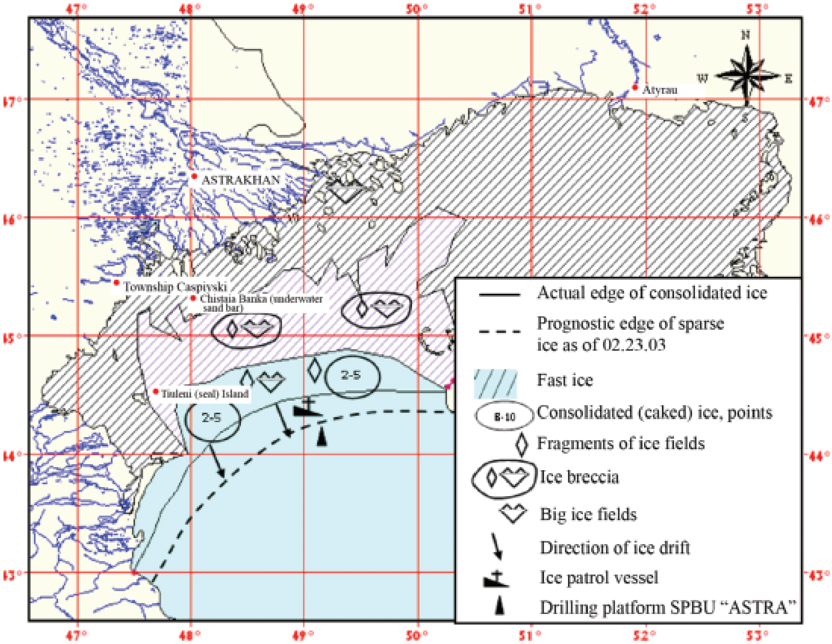

Figure 1. Ice Conditions on the North Caspian by the data from the artificial earth satellites (AES)

However, the problem of the present-day studies of hydrometeorological regime on the whole and the peculiarities of hydrological processes on the North Caspian in winter season is far from solution. To implement these objectives all necessary conditions have been created at theHydrometeorological Centre of the Caspian Flotilla. This makes it possible to perform systematic work on upgrading the calculation tech

ICE CONDITIONS ON THE LOWER VOLGA AND THE NORTH CASPIAN SEA DURING THE MODERATE WINTER OF 2009–2010 [4]

ABSTRACT

The water area of the sea port, channel and a part of the Caspian Sea to the North of the 44th parallel is covered with static ice every year. Ice forming usually starts in the second half of December. The ice cover reaches its most intensive development at the end of February. In the first half of March the ice breaks. In the second part of March the water area as a rule is free. The duration of ice period varies on a wide scale.

INTRODUCTION

Navigation is all-year-round in ports Astrakhan and Olya. In the 60s and 70s of the last century occasional ice-breaker pilotages of the fishing fleet were carried out in the winter period with the help of tow-boats with ice enhancement which belong to the fishing port of Astrakhan. In 1978 several powerful Finnish ice-breakers of river class – "Kapitan Chechkin", "Kapitan Krutov", "Kapitan Bukaev" – and marine class – "Kapitan Izmailov" (Figure 1) and "Kapitan Radzhabov". The efficiency of ice-breaker pilotages has increased since that time. The freight flow to Iran and ports of other states of the Caspian region rose in the 90s. Ice-breaker pilotages have become regular since the establishment of Marine management of port Astrakhan.

The convoy consisted of 6–8 vessels that went into the sea from port Astrakhan. The same number of vessels went along the channel into the port. River ice-breakers were rented by the Marine management from JSC "Volgotanker". Ice-breakers "Kapitan Chechkin" and "Kapitan Bukaev" were signed off to SI "Marine management of port Astrakhan" in 1998. "Kapitan Krutov" (Figure 2) was given to one of the ports of the Black Sea basin. It became necessary to enhance ice-breaker supplies as a result of increasing ship flow and extra fleet in the Caspian Sea. The ice-breaker "Kapitan Chadaev" rented from JSC "CC "the Volga Steam Navigation", was called for assistance to the 2 left ice-breakers during another 2 years. This ice-breaker was given to Archangelsk in 2001. The preparation for the winter navigation of 2009–2010 was

[4] Ice conditions on the lower Volga and the North-Caspian sea during the moderate winter of 2009–2010 / P.I. Buharitsin // Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions July 10–14, 2011 Montréal, Canada.

initiated long before stable negative atmospheric temperatures and freezing-over in the water area of port Astrakhan, Volga- Caspian ship canal (VCSC) and Astrakhan roads. In the period between September and November the Federal Establishment "Astrakhan Seaport Administration" got the information from ship-owning companies on the number of vessels to work in the Caspian basin with the call in VCSC and ports Astrakhan and Olya during the forthcoming winter navigation.

Figure 1. Finnish ice-breakers of marine class – "Kapitan Izmailov"

123 vessels were claimed from 23 shipping companies which 50 % exceeded the number of ships and companies claimed for the winter navigation of 2008–2009 and 4 times exceeded the number of vessels claimed for the navigation of 2007–2008. Ship owners partly didn't present the information in time claiming that they didn't know which vessels were going to stay in the pool and which were going to work in the Southern and middle parts of the Caspian Sea without putting in the ports Astrakhan and Olya. The major part of vessels had the sign of ice strengthening category in their symbols. This sign allows both to follow an ice-breaker and to navigate on one's own (under specific density and thickness of ice). Most vessels (53) were from 20 to 30 years of age and 39 vessels – more than 30. Some of them had gone through renewal procedure of the hull under the control of qualification committees.

Figure 2. Finnish ice-breakers of river class – "Kapitan Krutov"

According to the results of hydrographic surveys of the limiting areas of VCSC, the submersion 4,5 m remained for the vessels. These results were presented by the navigational hydrographic maintenance service of Astrakhan branch of Federal State Unitary Enterprise "Rosmorport". In the marine part of the channel (from the 138th to the 170th km) new illuminated ice buoy-cigars were found. Corresponding meteorological forecast was inquired and received for the forthcoming autumn-winter period. Two inline ice-breakers from Astrakhan branch of Federal State Unitary Enterprise "Rosmorport" were prepared for piloting the vessels. These ice-breakers were "Captain Bukaev" and "Captain Chechkin" that are of "M-SP" class of the Russian fluvial register. They can work in the solid ice up to 70 cm thick and incoherent ice up to 1 m thick.

On November, 30 2009 the captain of the sea port "Astrakhan" issued the an order № 149 "On winter navigation of 2009–2010 in the water area of port "Astrakhan", VCSC and Astrakhan roads". The order claimed the beginning of winter navigation 2009–2010 from December, 1 2009. It also determined the measures for the organization and management of ice-breaking piloting including the establishment of headquarters on ice-breaking operations. The position of the head of ice-breaking operations headquarters was given to the captain of sea port Astrakhan M.A. Abdulatipov. Members of Astrakhan region authority, state control bodies, Association of shipping agents and ship owners of Astrakhan region, employees of FSI "Astrakhan Seaport Administration" and Astrakhan branch of Federal State Unitary Enterprise

"Rosmorport" as well as captains of the vessels "Captain Bukaev" and "Captain Chechkin" were included. They directly provided the operation of ice-breakers (Figure 3).

The key task of the headquarters was providing effective emergency-free operational activity of vessels which does not allow dead time during the work under ice conditions.

Figure 3. The Caravan court in Volga-Caspian channel

Apart from that, the following tasks were set before the headquarters:

– collecting and summarizing the data on hydrometeorological environment in port Astrakhan, VCSC, Astrakhan roads and designing suggestions on the organization of ship operation in these areas;

– building vessel convoys for their piloting in ice conditions according to the enquiries of vessel captains. These enquiries should be sent via agent services;

– coordination of partnership with frontier authorities of FSS in the Republic of Kalmykia and Astrakhan region, Federal State Unitary Enterprise "Rosmorport" and other institutions for executing vessel navigation in the convoy;

– giving the ship owners and their agents the information on the conditions of organizing the piloting;

– providing the information and announcements on winter navigation via mass media as well as on the web-site of Federal Establishment "Astrakhan Seaport Administration";

– providing rational disposition of ice-breakers;

– limiting the time of inefficient dead time related to landing and embarkation of pilots, building convoys, preparation of vessels for leaving a port, managing mooring operations and so on.

The key principles of the operation of the headquarters were:

– equality of ports without priorities;

– demonstrativeness and informative content of ice supplement;

– regular succession of piloting according to Paragraph 31 of Common rules of navigation and moorage in seaports of Russia and on the ways to them.

The time needed to approach the ice edge is taken into account when forming convoys if there are no vessels having the right of way.

The order of setting the limits for ships according to the conditions of ice navigation was determined in the order.

On December, 7 2009 in Federal Establishment "Astrakhan Seaport Administration" joint conference was conducted with the representatives of Federal State Unitary Enterprise "Rosmorport". The problems of providing the safety of navigation in the water area of the port during winter navigation were being discussed. The order of ice-breaking piloting, business hours of ice-breakers, the number of vessels in the convoy and places of bunkering were defined.

On December, 11 2009 an extended session was carries out on the questions of winter navigation under the headline of captain of seaport Astrakhan. Representatives of Astrakhan authorities, Establishment "Astrakhan Seaport Administration", Federal State Unitary Enterprise "Rosmorport", state control bodies, ship owners and stevedoring companies were taking part in it.

With the setting of ice cover in the water area of port Astrakhan, VCSC and Astrakhan roads obligatory ice-breaking piloting was introduced from 00 o'clock on December, 24 2009 with the order of the captain of seaport Astrakhan from December, 23 2009 № 72-r. The vessels not having the sign of ice strengthening in the symbol of ship class were not allowed to navigate in the mentioned areas including as part of a convoy.

With the decision from December, 25 2009 a ban was imposed on the inclusion into the ice convoys of the vessels older than 30 years except for the ones that had gone through hull renewal procedure under the control of Russian marine register of navigation and other classification committees which are members of IACS.

The ship owners were informed in advance about the forthcoming age-related and other changes in October and November 2009 with circular notes which suggested planning the work of vessels falling under the limits beyond the bounds of ice edge.

Two inline ice-breakers participated in the work on piloting the vessels – "Captain Bukaev" and "Captain Chechkin". Controlling and operating staff from the department of ship organization and management were collecting information and working out the daily plan of ice operations.

On January, 18 2010 a storm warning on the forthcoming progress of ice processes, intensive ice drift and its stratification due to arctic air outbreaks from North-West and strengthening of Eastern and South-Eastern wind was received from the hydrometeorological center of the Caspian fleet. Intensive ice hummocking and stratification as well as its sinking to the bottom as a result of its own weight and forming of grounded hummock were expected in VCSC. Increasing water level was expected under storm surge 1–1,5 m in the North-Western part of the North-Caspian.

Progressing ice formation, constant negative atmospheric temperatures and a storm warning led to an emergency business meeting of the headquarters of the ice-breaking operations on December, 19. The meeting concentrated on designing the measures that could provide safe ice-breaking piloting with regard of hard ice conditions. As a result, a decision was taken to direct the vessels, that would gather on Astrakhan roads for filling up the supplies and waiting for the improvement of weather conditions, to other ports of the Caspian Sea. Ship owners and captains were informed about this decision and corresponding coastal warning was announced.

At the same time in the open area of VCSC from Bolshoi povorot to Malyi povorot (the 2nd bend of VCSC, 151st – 170th km) ice formation was progressing due to constant Eastern winds 12–18 and more m/sec of strength, retaining for 5 days, and freezing temperatures at night. Within navigable waters of VCSC intensive compression, hummocking and stratification, near Malyi povorot – intensive ice movement were observed. In these conditions following an ice-breaker was impossible. Ships with power-plants of low capacity or in ballast had to be tugged after the ice-breaker to avoid throwing the ice to the channel edge and possible hull damages. Ice-breakers were working 100 % hard. Sometimes they had to resort to ramming ice-breaking (Figure 4).

The second complicated area was a closed part of the channel near Iskustvennyi island (from the 100th to the 135th km of VCSC) with the ice of 10 points of mashing character. In this area the shipping was impossible without being tugged by an ice-breaker. The construction of the channel's bottom in this area contributed to massive collection and stratification of ice which made this area a heavy road even for a single ice-breaker. Every piloting took 3 hours and more.

Despite round-the-clock work of the ice-breakers, they didn't have enough time to pilot all the vessels in these areas to say nothing of piloting the ships along the channel to Astrakhan and from Astrakhan. The most difficult ice conditions were observed from the last ten days of January to the first ten days of March 2010. Ice edge reached 44°18′ North latitude. Suchlike situation was also observed during winter navigation of 2002–2003 when ice breaking piloting began on December, 10 and ended on March, 13.

By the beginning of February 2010 ice conditions became considerably difficult as a result of sharp worsening of weather (storm wind of Eastern direction more than 20 m/sec of speed with later change of direction to the West, fall of temperature below -20 °C at night). The situation was characterized with intensive ice formation, movement of ice fields, change of ice structure. The ice became harder. These factors resulted in serious difficulties during ice-breaking piloting. Ships began to gather in the inlets and outlets waiting for ice-breaking piloting. Some days, ice-breakers could not work in the open area of VCSC at all because of meteorological conditions. During this period, they were tugging the ships through a difficult area near Iskusstvennyi Island. The number of vessels waiting for ice-breaking piloting on Astrakhan roads to ports Astrakhan and Olya reached 50. The same number of ships were expecting piloting in ports Astrakhan and Olya to VCSC up to the 100th km (above the dyke near Iskusstvennyi Island) and between the 135th and 145th km (below the dyke).

Figure 4. The most difficult ice conditions were observed from the last ten days of January to the first ten days of March 2010

The captain of the port was onboard one of the ice-breakers and controlled ice-breaking operations on Astrakhan roads on his own. Later representatives of the headquarters of ice-breaking operations were constantly onboard ice-breakers and coordinated their work. As a result of difficult conditions the headquarters gathered for business sessions every day from 9,00 am to 16,00 pm.

Weather forecast and information from ice-breakers and captains of ships waiting for piloting was listened to at the conference. Direct connection was set up between captains of ice-breakers and headquarters representatives onboard. They analyzed the situation, worked out the decisions as how to implement ice-breakers rationally and avoid emergencies.

The headquarters recommended the ship captains to follow and ship owners (or agent companies) to direct the vessels to fill up the supplies or to wait for the improvement in the ice conditions in other ports of the Caspian Sea. Critical situations could be caused, apart from other factors, by the lack of fuel and other supplies on board.

Some of the captains took advantage of that opportunity. However, the majority of the ships were staying on Astrakhan roads with the risk to run out of fuel and food. At the same time the captain of port Astrakhan was constantly receiving panic radiograms with requests to include a vessel into a convoy for ice-breaking piloting right off. Ship owners, that had directed their vessels into other ports to refill the supplies, were grateful to the headquarters for timely given recommendations.

At the beginning of March ice formation stopped with growing temperatures. Wind strength became moderate and there emerged the opportunity to pilot the vessels unhindered. The captain of seaport Astrakhan issued the order № 9-r from 16/03/2010. According to it, from March, 18 ice-breaking piloting and the validity of the orders related to winter navigation were terminated. Independent navigation (without ice-breaking piloting) was allowed in the water area of port Astrakhan, VCSC and Astrakhan roads. At the same time the ice breakers were in level readiness for giving all the necessary aid to the vessels: one in port Astrakhan and the other – near the 150th km of VCSC where, as a rule, there is drifting ice in spring.

The captain of port Astrakhan stroke down with the order from March, 22 2010 № 41 the order from November, 30 2009 № 149. From 00 o'clock 23/03/2010 winter navigation was considered illegal.

From December, 23 2009 to March, 17 2010 the ice-breakers carried out 32 piloting operations and accompanied 542 vessels which was 10 % more that during the previous winter navigation. The number of the piloted vessels could have been much more considerable if there were one or two more inline ice-breakers. Maximum length of ice-breaking piloting comprised 140 miles. Maximum latency for the ice-breaking piloting reached 19 days for leaving the port and 40 days – for making the port.

All in all, 149 carriers were working during winter navigation in the Caspian pool with landing in VCSC and ports Astrakhan and Olya. 1090,3 tons of cargo was transported.

7 incidents with vessels were recorded during winter navigation. These were generally losses of anchors with cables while waiting for ice-breaking piloting

on Astrakhan roads (4 cases). Later in two cases the anchors were found by the members of the crews and fixed in the regular places. There was also setting down of motor ship "Ulus Star", hull damage of "Langepas" and a collision between motor ships "Linda" and "Sail Duke" that stemmed from insufficient distance between the vessels while navigating within a convoy.

Maximum ice thickness in the marine part of VCSC reached 50 cm, in some places – 1 m and in hummocks – up to 1,5 m. Grounded hummocks up to 8 m of height were observed. Ice thickness reached 25–30 cm, in layers – up to 50–80 cm in the coastal area of the channel. All the necessary information for navigation in the ice was timely passed to ship owners and navigators.

Unfortunately, there are unsolved questions in port Astrakhan. They directly concern the organization of ice-breaking piloting and the work of port terminals. This is primarily related to ice-breaking piloting. The two ice-breakers available do not manage with the growing number of vessels participating in the ice navigation. This problem has been raised time and again in at various levels. But after winter navigation it is forgotten. The problem arises again when vessels are making giant queues waiting for ice-breaking piloting.

It is also necessary to solve problems with port ice-breakers which could do the ships this or that service, for instance, moving the vessels on berths and roads or providing safety measures while navigating in ports. It is also possible in this case to tackle the opportunity of their work in the area between ports Astrakhan and Olya. They could offer the service of keeping ice cracks for three ferry passages in the given area in an appropriate state.

Besides, one needs to continue the work on development of VTMS with the aim to control the vessels on Astrakhan sea roads; equip ice-breakers with the means control of their location (SMS "Victoria") and allow access to these means for the captain of the port; to tackle the equipment of ice-breakers with modern navigation systems that meet the demands of international conventions on the safety of navigation.

INVESTIGATION OF THE ICE REGIME OF THE EASTERN PART OF THE CASPIAN WITHIN BACKGROUND ECOLOGICAL INVESTIGATION PROGRAM AT YUZHNY JAMBAY-YUZHNY ZABURUNJE [5]

ABSTRACT

Caspian Sea is featured by a great diversity of ice processes with seasonal ice cover. It is serious natural threat for economic activity of man in the sea (fish and seal production, ship industry and in recent years, oil exploration at the Caspian Sea). Ice cover is considerably restricts the man activity and is of real threat to the safety. In this connection the investigation of the ice processes is both of scientific and practical interest. Exploration works recently held in Russia and Kazakhstan in the shallow waters of the northern part of the Caspian Sea (including winter periods) urge scientists to international cooperation in the field of contemporary winter hydrogeological and ice processes in the Northern Caspian Sea. Necessity and timeliness of the ice investigations is also connected with the fact that character and intensivity of the ice processes in the sea considerably changed due to the sea level rising for more that 2 meters during the last 30 years (since 1978). In the present work we applied the investigation data obtained in the period since December 2007 up to March of 2008 within the ice regime investigation of the Caspian Sea in the frame of the background ecological investigation at the Yuzhny Jambay – Yuzhny Zaburunje.

GENERAL DATA ON THE ICE REGIME

During the cold seasons of year, the eastern part of the Caspian Sea is under the prevalent impact of the spur of the Siberian anticyclone. In this connection the atmosphere pressure is higher here than in the western part which results to the great reoccurrence of the winds of the eastern rhumbs. To the north of the Caspian Sea there are Kazakhstani semi steppes and steppes which get cold rapidly in fall. There are early and severe frosts in winter. That is why the eastern coast of the Caspian is the coldest region of the whole Caspian Sea area. And here the coldest area is the northern part of the eastern coast side of the Emba river.

[5] Investigation of the ice regime of the eastern part of the Caspian within background ecological investigation program at yuzhny jambay- yuzhny Zaburunje / E. Ayazbaev, P.I. Buharitsin // Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions July 10–14, 2011 Montréal, Canada.

The first ice appears as ice fat, gruel or rind (primary kinds) and marked at the coastal shallow waters in moderate winters. It takes place in the beginning of November in the are of Zhilaya Kosa and in the area of the Burunchuk Cope in the middle of November during the night frosts. The first appearance of ice is not stable usually – it melts during the daytime. Stable freezing comes in seven days averagely. Fast ice is formed. At the end of November, the edge of the fast ice lays along the isobath of 2 meters in 3 – 8 miles from the coast. Almost the whole eastern part of the Northern Caspian Sea is covered by fast ice in December – February.

Ice appears in October in anomalously severe winters. So on the 31st of October in 1960 the edge line of the fast ice was marked at the meters of depths according to the data of the ice air observation. The first ice appears only in December in anomalously mild winters. For example, the first ice was observed on the 11th of December 1939 in the south-eastern part of the coast between Burunchuk Cope and Balashovsky sand islands [1]. It is necessary to note that each second winter in average ice can disappear completely after the first appearance of the ice and even after the ice was completely frozen and then ice can appear again.

In some winters such complete ice freezing and complete melting of the ice happens twice and even three times.

Prevailing eastern winds bring great volume of sand and dust from the kazakhstani steppes. It impacts a lot on the ice albedo and facilitates fast spring destruction of coastal fast ice.

The areas of ice pressure and loose appear under the impact of the strong winds. It results in intensive movements, formation of ice clearings, ice holes and ice blocks. The processes are intensive during the spring ice melting. The coastal area of the sea with the depth of up to 40 cm is frozen down to the bottom and ice lies on the ground up to 10 km from the coast. Spring destructions of the fast ice begins with the melting water on the ice and flaw lead then penetrating flow lead or vast coastal ice hole 10–20 km of width is formed. In moderate winters spring destruction of the fast ice comes in March and and clearance takes place in the end of March – beginning of April. Complete clearance of the sea from ice take place in the second half of April in anomalously severe winters. The area of the ice cover is inconsiderable by the end of February in mild winters. So, on the 18th of Fubruary 1946 the fast ice was marked only at the north-east in the area of Emba river offing and the edge of the floating ice was spread from Balashovsky sand islands to north-west, the Borozdinny island. There is almost no ice at the eastern part of the Caspian Sea in March during mild winters. Average days with ice is 150 days in the north, 125 in the south. During the mild winters it is 130 and 110 correspondingly and 170 and 140 during the severe winters.

Maximal thickness of the fast ice is in the end of February – beginning of March. It fluctuates from 48 up to 96 cm in the area of Zhilaya Kosa and from 24 to 65 cm near the Burunchuk Cope.

Maximal thickness of the ice at Zhilkosinsky road was 90 cm observed on the 8th of March 1930. it was the maximal thickness of the ice of natural (thermal) building-up registered during observations at the Caspian Sea. Thickness of the ice of 96 cm is marked not in the sea but in the former bay separated from the sea.

During the destruction period the fast ice is turned into drifting ice. It may drift westward under the impact of the eastern wind and forming vast areas of clear water at far east of Northern Caspian Sea. There is still a lot of ice at Guryev ice furrow. It covers vast areas and quite solid. The ice starts drifting towards eastern coast, hummock and build-up on shallow waters under the influence of the piled-up western winds. Increase of the level during the piling-up results in ice edges occur on the coast and penetration of the ice into the coast for several kilometers down.

Drift speed of the solid ice reached 0,5 m/sec at strong wind (7–8 points). Drift speed of separate ices is 1 m/sec at the wind of 4–5 points of strength.

There is no solid snow cover formed on the ice usually. The snow accumulates in the form of snow erosion ridges and spots with the thickness of up to 10 cm. There are snow piles with the thickness of 40–50 cm are formed at windside toros and rows of toros.

DYNAMIC PROCESSES IN THE ICE COVER

Breaking and clashing of ice is the result of uneven drift of separate ice formations. It comes to the ice cover deformation. Ice deformation is buildups, sublayers and toroses and results in considerable thickening of the ice cover. Visual evaluation of the ice cover torosity level is very complex task considering different age composition of the ice, different time of toros formations and a great diversity of toros forms. Along with it, this element of the observations is one of the most important for evaluation of the fast ice status and solidity of the floating ices. Rows of thick toroses where ice masses forms, one solid ice is of draft which exceeds the above water height by 4–7 times and often is an invincible obstacle for both ships and icebreakers. Torossing ice are of great destruction power and is really dangerous for ships, different kinds of hydrotechnical facilities, piers, platforms and etc.

Fast ice especially near the edge is often characterized by a row torosity. Floating ices while drifting are subject to multiple torosity. This torosity of chaos character where separate hummocks and ropacs (standing floes) come with rows of toroses of different directions. In the conditions of shallow waters of the Northern Caspian Sea the drifting toros ices are often cast aground. It is also facilitated by rundown piled up sea levels characteristic for this part of water area. The result is grounded ice – toros ice formations casted aground [2, 4].

Increase of the oil exploration activity of Russia and Kazakhstan companies with foreign partners at the Northern Caspian Shelf requires serious scientific, ecological and technical approaches. The results of the cooperated ice investigations were applied to practice. So, reconstruction of typical immersible drilling barge was performed for the needs of OKIOK Kazakh company (Offshore Kazakhstan International Operating Company) in 1999 in Astrakhan. The barge was adopted for unique natural and geological conditions of North-Eastern Caspian Sea. Submersed foundation and barge boards were modified to resist ice loads which had been studied and analyzed for five years. Computer modeling was performed. As the result the area of the barge was increased twice, special ice diverting device from both sides of the barge. Diverting devices were modeled to resist ice pressure. A system of thick metal piles (depth of burial up to 20 meters) are considered from the barge both sides at the place of barge stop in the sea. They are assigned to restrain the pressure of the drifting ice and activisation of toros formation at the far accession to the drilling platform. As the result artificial grounded hummocks are formed which are reliable protection for the platform from floating ice. Forecast of the ice floating direction under the impact of the wind and streams is very important. Lack of consideration of these factors can lead to emergency. So, we can analyze the situation in the area of Kashagan facilities in December 2007. The situation reached the critical point on the 16th of January when the access channel was blocked by an ice 1,5 meters of thickness as the result of storm and intensive ice movements. The ships were paralyzed for several weeks and whole personnel was evacuated.

ICE CONDITIONS IN THE 2007/2008 COLD PERIOD

According to the severity conditions, the 2007–2008 winter (the forecast prepared on October 10, 2007, ice conditions in the Lower Volga and Northern Caspian) was in whole expected to be close to average multiyear values – "moderate winter" (Table 1).

Table 1

Classification of winters in the Northern Caspian according to the extent of their severity (accumulated temperature, Σ-t˚daily mean C in Astrakhan port) [3]

Very severe winter	Severe winter	Moderate winter	Mild winter	Very mild winter
More than 900˚C	900–700 °C	700–400 °C	400–100 °C	100 °C and less

The amount of negative daily mean temperatures in Astrakhan port over the winter was –544,9°, which meets the "moderate" winter criterion; in Peshniy and Zhambai (Kazakhstan) –922,1° and –841 accordingly which meets the "very severe" winter criterion (Table 2).

Table 2

Accumulated temperature over the 2007–2008 winter in the Northern Caspian settlements

Settlements	Nov	Dec	Jan	Feb	Mar	The amount of negative daily mean air temperatures (accumulated temperature) over the winter
Astrakhan	since 07.11 –28,7	–100,3	–274,9	–141,0 till 22.02	–	–544,9
Peshnoi	since 07.11 –62,3	–209	–422,2	–228,6 till 23.02	–	–922,1
Zhambai	–51	–190	–400	–200	–	–841

In shallow waters of the northeast part of the Northern Caspian initial ice forms as a nilas (5–10 cm thick) appeared on November 23.

According to satellite data, the ice edge in the east of the sea passed in the 52nd meridian (exploration area) on December 13, then it turned to the west along the northern coast till the 50th meridian; a fast ice belt was formed in depths up to 1–2 m. The ice edge moved to the west, southwest to 5-meter depths by 17.12; the fast ice belt had also formed along the northern coast till the 50th meridian at the depth of 1–2 m.

By 18.12 the ice processes had strengthened and the ice edge moved towards west to the 49th meridian; there was no ice in area 21050. By the end of the month the entire northeast part of the Northern Caspian was fully covered with the fast ice belt (it was in the form of drifting ice packs in area 21050); the ice edge moved from the Mangyshlak gulf along the 45th parallel to the west coast (Sand bank).

In the beginning of January, the frost strengthened (in Astrakhan the minimal temperature on 04.01 was up to 23,0 °C, in Atyrau from 02.01 till 13.01 minimal night temperatures were below 20,0 °C, the minimal temperature was marked on 12.01: –27,5 °C).

The fast ice belt boundary on January 9 went along a 5-meter isobath; the exploration area was fully covered with stagnant ice. The ice edge was 22 miles to the south from the Astrakhan beacon location along the western seashore and 10-meter isobath to Izberbash port area. The boundary of drifting ice went along a 20-meter isobath.

The ice thickness in the first decade of January 2008 was 45–55 cm in the northeast part and 25–45 cm in the northwest part. The level ice reached maximal thickness over the season in the second decade of January which was 55 cm in the northwest of the sea and 60 cm in the northeast (Table 3).

Table 3

Ice thickness at Jambay, cm

December, 2007			January, 2008			February, 2008			March, 2008	
1st decade	2nd decade	3rd decade	1st decade	2nd decade	3rd decade	1st decade	2nd decade	3rd decade	1st decade	2nd decade
–	–	25	35	45	55	55	60	55	50	40

During the 2007–2008 winter period the lowest temperatures were marked from 05.01 till 28.01 and from 01.02 till 22.02 along all coasts of the Caspian Sea. Low temperatures along the east coast retained till 28.01 and repeated in February till 21.02

In the northeast of the Northern Caspian and exploration area the fast ice belt broke and drifting grey and white ice was carried away into the deep-water part of the sea on February 1 due to strong northwest winds; cracks appeared in the ice in the exploration area.

Only in the end of February the thermal breakdown of ice started in the Northern Caspian.

On 06.03 the fast ice belt retained at the 1–2 meter depth in the exploration area, there was grey and white drifting ice in the form of pieces of ice fields and small ice fields as well as large and small ice pieces of various concentration; the extent of ice destruction was 1 point.

The boundary of these drifting fields reached the 20-meter isobath. Single drifting fields reached the Medium Pearl bank.

On March 8 the Pearl island was freed of ice, on March 10 – Clear Bank and Kulaly islands, on March 12 – Ukatniy island.

By the end of March the exploration area was freed of ice; the drifting ice retained only in the northeast part of the Northern Caspian, concentration of drifting ice (large and small ice pieces) was from 1 to 4 points in Guryev Borozdin and from 4 to 8 points in the east, northeast of area 21120. Also there were grounded ice hummocks among clear water. The northeast part of the Northern Caspian in 2008 was completely freed of ice on April 1.

Photos received from satellite allowed to generate maps of the actual position of ice edges and properly evaluate characteristics of the ice cover (Figures 1–3).

Figure 1. Ice status as per 29 of December 2007

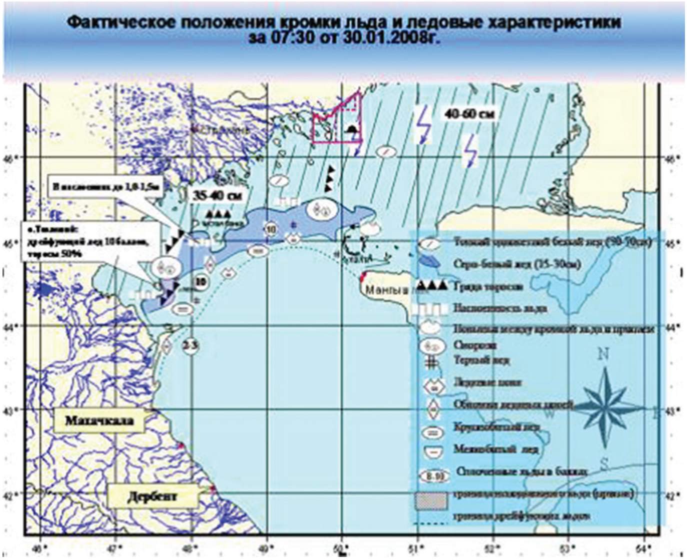

Figure 2. Ice status as per 30 of January 2008

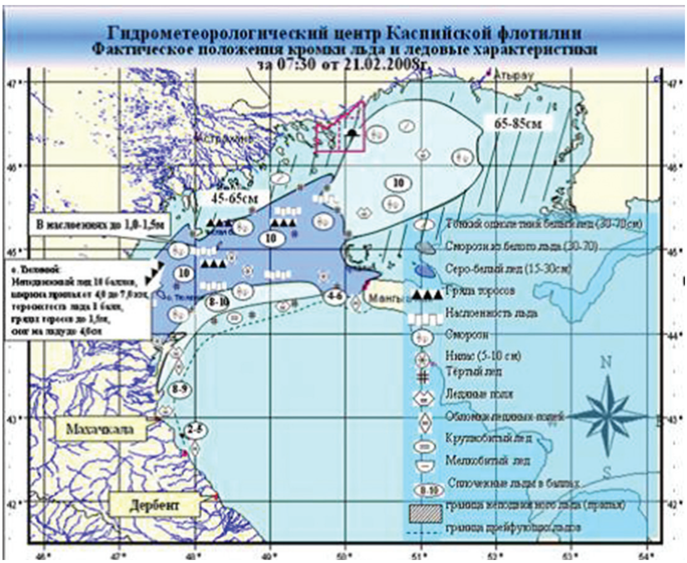

Figure 3. Map of factual ice edge location and ice characteristics as per 21 of February 2008

FIELD INVESTIGATIONS

Ice prospection including observations over the thickness change and thickness of drift and fast ice in winter 2008 (with the help of tool measuring) was carried out according to the Background Ecological Investigation Program at Yuzhny Jambay and Yuzhnoje Zaburunje. Besides, investigation of the ice regime included investigation of the ice morphometry and thickness at the investigation stations; average ice thickness; solidity of ice and ice cover in the whole; relation of ice movement and wind and sea waves direction; study of the toros formation (pressure, movements, lean-on, shift, ice size isolated from edge, velocity of their movement). There were an air investigation of the ice regime of the Caspian by the helicopter (ice observation investigation). There was also application of artificial satellites (space images) and land vehicles (airboats) at the stations which location is given in the Table 4.

Table 4

Location of the ice regime observational points

Serial number	Station type	X	Y
1	Investigation of the ice regime	46°20′	49°43′
2	-«-	46°22′30″	49°47′
3	-«-	46°20′30″	49°52′
4	-«-	46°16′45″	49°53′
5	-«-	46°30′	49°56′
6	-«-	46°14′30″	49°52′

THE LABORATORY INVESTIGATION RESULTS

Ice kerns were taken for chemical composition investigation during the ice air investigation. Besides, study of the ice solidity was carried out with the help of the ice samples.

Data on the chemical composition of water obtained from the ice kerns are presented in the Table 5. Chemical analyses were carried out in the laboratory of Monitoring Ltd in Atyrau.

The table shows the content all ingredients is lower the allowed values of MAC. Water is fresh according to the relation of the dry residue from ice kerns.

pH of water in the upper, medium and lower parts of the ice changes from 5,21 to 5,29. According to the accepted classification of pH the water is referred as slightly acidic which is connected with atmospheric precipitation on the ice surface.

Table 5

The results of the chemical analysis of water of ice kerns at the investigation stations (Maximal Allowable Concentration for commercial fishing in brackets)

Serial number	Substance	Station number and location					
		№ 1 46°20′ 49°43′	№ 2 46°22′30″ 49°47′	№ 3 46°20′30″ 49°52′	№ 4 46°16′45″ 49°53′	№ 5 46°30′ 49°56′	№ 6 46°14′30″ 49°52′
1	Salt ammonium, mg/l (0,5)	0,14	0,12	0,16	0,14	0,15	0,14
2	Nitrites, mg/l (0,08)	0,0148	0,0146	0,0152	0,142	0,144	0,146
3	Nitrates, mg/l (40,0)	0,102	0,108	0,106	0,104	0,104	0,104
4	Chlorides, mg/l	501,5	502,3	503,2	502,4	501,6	501,6
5	Sulphates, mg/l	118,4	120,4	119,6	118,6	118,8	118,6
6	Hydrocarbonates, mg/l	77,5	78,0	76,8	77,6	77,8	77,6
7	Hardness, mg-eqv/l	11,05	11,08	11,06	11,04	11,06	11,04
8	Calcium, mg/l (180)	114,8	115,2	114,6	114,5	114,7	114,6
9	Magnesium, mg/l	64,7	66,8	65,6	64,6	64,8	64,8
10	Dry residue, mg/l	1099,5	1100,0	1098,0	1099,6	1099,8	1099,4
11	Σ Na + K, mg/l (390)	172,2	174,0	173,1	172,6	172,4	172,4

ICE SOLIDITY CHARACTERISTICS

Physical status of the ice cover as a rule was determined by slight minus air temperatures and often above zero. Minus temperatures from –1,1…to –4,5 °C were marked only on the ice cover surface.

Ice salinity varied from 0,1 to 0,4 ‰.

Liquid migration from the surface layer considerably impacts on the ice solidity decreasing its value to 830–850 kg/m^3 in the layer. In the middle and lower layers there is texture stratification strongly marked. It depends on the content of air and the solidity values vary in the limits of 870–900 kg/m^3 [5].

Conditions of the ice formations with often warming up to the temperature which is close to 0 °C considerably impact on the ice texture features. Increase of liquid content phase up to the maximal values with the following migration during the thaw favors to development of secondary porosity. Stratified ice forms in the conditions of abundance of air pores. Stratified ice consists of semi-clear and not clear layers with not strongly marked whitish shade.

The layer becomes loose and of milky-white color when complete slippage of the liquid phase from the surface layer take place. Analysis of the structure show that ice forms of anisomerous isometric crystals 2–10 mm of size which is typical for such ice types as A6 and Б6 (Sea ice…, 1977).

Vertical development of fine-grained crystals along the basic plain occur during the most stable ice formation period. The result is ice layers of A4 and Б4 types formed.

Data on average and extreme values of ice stability of the area under investigation at the bending are given in the Table 6 (upper, medium and lower layers were investigated).

Table 6

Average and extreme values of ice solidity at bending (σ bending), MPa

Characteristic	Samples				Average for layers			Ice floe
	upper	medi-um	lower	all layers	upper	medi-um	lower	
Average value	0,87	0,80	0,68	0,78	0,85	0,79	0,72	0,84
Maximum	2,17	2,16	1,62	2,17	1,93	1,53	1,77	1,77
Minimum	0,01	0,01	0,01	0,01	0,10	0,10	0,09	0,09
Quantity of measuring	191	193	169	553	112	112	110	112

Minimal values of the ice solidity vary from 0,01 to 0,10MPa at the average value of 0,09MPa. Maximal values are from 1,53 to 2,17MPa at the average value of 1,77MPa.

Performed investigations and analysis of the obtained results shows that the most favorable condition for stratified ice formation is prevalence of piled-up south-eastern wind of normal direction for the coastal line.

Formed toroses are referred to blocking and stratified. They form owing to stratification of blocks one on another and their underspaces.

CONCLUSION

Such complex field investigation of the ice cover in the eastern part of the Northern Caspian has not been conducted the last 15–20 years.

On the basis on the submitted data on the ice cover observations in the report one can judge about the complexity, diversity and ambiguity of the ice processes on the investigated area.

Winter ice regime is quite complex and ice processes are of real threat for navigation and all possible hydro technical and other engineering facilities located on shore and especially on the Northern Caspian shelf. Design, construction and emergency free operation of the drilling units in the investigated area depend much on the adequate evaluation of the ice factor and adequate application of the data that we have today on ice regime in the given part of the Northern Caspian in the engineering.

Analysis of the data obtained during the expeditionary investigation of the materials at the contractual territory of Jambay Ltd. (Yuzhny Jambay and Yuzhnoje Zaburunje) in winter 2007/2008 testifies that ice processes in the area of investigation were characteristic for the eastern part of the Northern Caspian.

The total of average minus temperatures in winter in Astrakhan was minus 640°C (indicator of moderate winter). And in Atyrau the value was more than 900°C which testifies about severe winter.

Maximal thickness of even ice of thermal building-up in winter was 40–60 cm and at the same time the ice thickness in the western part of the Northern Caspian did not exceed 35 cm.

Border of the fast ice and edge of the floating ice changed their location under the influence of winds and streams. Ice movement took place at the wind strengthening of any direction including storms (up to 12 and more m/sec). Stratification of ice prevails for thin ice with thickness of less than 35 cm. Hummocking prevail in more thick ice (thickness of more than 35 cm).

Unfortunately, investigations of the ice regime of the Northern Caspian were closed completely in the recent years due to well known circumstances. At that the reduction of works was carried when Caspian Sea level rose intensively. It also influenced ice processes mobility (drift character, toros, ice thickening, ice surface area, ice appearance terms, sea clearing, etc).

Drift and movements of ice in northern shallow part of Caspian Sea are able to considerably influence on people's economic activity. Moreover it is found that small-scale zones of hypoxia at shallow water areas of intense ridges and hummocks are wide spread at winter season. It leads to sharp decline of species composition and reduction or even total extinction of whole phytoplankton biomass at suffocation areas.

Since more than 50 % of Caspian Sea shallow water areas (more than 200 sq km) are subjected to ice exaration (interaction of drifting ice and sea bottom) these processes can be considered as large-scale even being of seasonal character. It plays significant role for this water body environment. Beside pure mechanical movement of enormous subsoil masses the sea bottom, shore and island flora and fauna are depressed. Ice surface can make positive effect at spring period of destruction by cleaning seashore entry of Volga, Ural rivers and shore water shallow areas from faded last previous year vegetation. This reduces possibility of suffocation occurences at warm season.

Caspian ice is a serious danger for oil companies that plan to start oil extraction at explorated parts of northern Caspian sea waters in near future.

Taking into consideration the above mentioned we would like to consider the following:

– the possibility of continuation of regular cooperative visual ice air-monitoring along waters of Northern Caspian Sea (kazakh and russian part) with the following periodicity: each 10 day after established ice surface (Jan–Feb) and each 3–7 days at ice development period (Nov-Dec) and ice destruction period (Mar–Apr);

– feasibility of regular obtaining space (satellite) data of ice surfaces changes and its condition;

– possibility of research of physical, dynamic and other characteristics of ice at areas of planned installation of drilling units using helicopter and vehicles;

– development and implementation of new methods of ice prognosis.

For more detailed evaluation of ice impact on future production activities at Zhambay LLC contract territory the further research on ice processes is required.

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THE INFLUENCE OF SOLAR ACTIVITY ON LONG-TERM CLIMATICEVENTS IN THE NORTH CASPIAN REGION FOR THE PERIOD TILL 2017[6]

INTRODUCTION

During the design of long-term climatic forecast for the North-Caspian region the authors were using current data on the dependence of Earth climate from fluctuations of solar activity under the influence of total gravitating interaction between Earth, the Sun, the Moon and other planets. The authors were using present-day patterns of the dependence of Earth from circular vibrations of the solar activity and fluctuations of the rotation speed of the Earth under the influence of summary gravitational interaction between the Earth, the Moon, the Sun and other planets during the design of the long-term forecast of the extreme climatic changes in the North-Caspian region.

RHYTHMS OF THE SOLAR ACTIVITY AND THEIR INFLUENCE UPON THE LONG-TIME CLIMATE EVENTS IN THE NORTH CASPIAN REGION

In N.S. Sidorenkov's work [3] there are close connections between the rotation fluctuations of the Earth and changes in climate characteristics. In the periods of low-speed rotation of the Earth the repetition of the meridianal form of atmospheric circulation (C) in the first sector of the Northern hemisphere (from 50 w. l. till 80 e. l.) increases, and zonal (W and E) – decreases.

The mass of ice in the polar zones, tempo of growth of the global air temperature, total amount of cloudiness and precipitations decrease. The medium wind speed increases in the near-earth layer and evaporation from the surface and the sea.

In 1973 there began the period of faster Earth rotation, which will finish in 2005–2010. After that there will come the period of slow down Earth speed rotation, which will bring a new climate epoch, which will last for about 35 years (till 2040–2045).

The influence of the solar activity processes on the Earth climate was recorded more than two centuries ago and nowadays it is beyond any doubt . The basic cycles of the solar activity are the following:

– 11-year cycles (by Schwab-Wolf) are defined by the quantity of spots on the Sun surface. There the cycle is the time between two minimums of the sun spots. The duration of the cycle is from 7,3 to 17,1; the average one is 11,2 (the name 11-year

[6] The influence of solar activity on long-term climatic events in the north-caspian region for the period till 2017 [Текст] / P.I. Buharitsin, A.N. Andreev // Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions July 10–14, 2011 Montréal, Canada.

stems from it). Since 1755 every cycle has the ordinal number. At present the 23d cycle is going.

– 22-year cycles (by Hoil). During the succession of one 11-year cycle by another one, the polarity of the head and tail sun spot in each hemisphere of the Sun changes, which allowed Hoil to single out the 22-year period, consisting of even and odd 11-year cycles.

– 80-year ("century") cycles were recorded by A. L. Gansky. In 1939 Gleisberg counted the duration of the century cycles – 78 years. The existence of these cycles was confirmed by M. N. Gnevyshev.

– 190-year cycles ("indiction"). In 1948 L. L. Predtechensky recorded the cycle of the solar activity – 190 years. It was called indiction, which means "returning".

D.A. Bonov counted the duration of the indiction – 176 years (8 cycles of 22 years each).

The differences in magnetic properties of even and odd 11-year cycles define the differences of their influence upon the Earth climate. After the middle of 2007 the new 24-year cycle started. The cycle is even. Its influence upon climate characteristics appears in the following:

– the atmospheric pressure in the arctic zone decreases during the maximum solar activity and increases in the temperate latitudes;

– the zonal type of atmospheric circulation increases during the maximum of the solar activity;

– well-developed monopolar magnetic poles strengthen the meridianal type of atmosphere circulation during the even 11-year cycle;

– peaking of meridianal circulation in the middle latitude strengthens temperature contrasts with the intrusion of arctic air up to latitude 30–50 n. l. and it brings overall fall in the temperature.

NOTE:

taking into consideration the total quantity of the sun spots in the 11-year cycle, besides the basic one, they single out three more maximums of the activity:

– 1–2 years before the basic one;

– 1–2 year after the basic one;

– 5 years after the basic one.

Apart from that:

– monopolar magnetic poles on the sun surface are better developed on the recession curve and on the minimum of the solar activity of the 11-year cycles, which explains the presence of two maximums in atmospheric processes connected with the sector structure of the magnetic poles:

1) with the maximum solar activity;

2) not long before the minimum of the solar activity.

The influence of the solar activity upon the climatic characteristics is of regional character strengthening atmospheric processes in some regions and weakens in others. The change of the climate on the coast and the water area of the North Caspian region are of single direction. The temperature regime in Astrakhan, Tyuleny island, Kulaly island, Ganyushkino, Atyrau, Peshnoi, Fort-Shevchenko during 1938–2003 was changing synchronically. Periods of the sudden change in the temperature emerge simultaneously and have one trend – increase or decrease.

The use of many-year data of observations of atmospheric temperature in Astrakhan since 1836 allowed to single out the peculiarities of temperature regime from the 8th to the 23rd 11-year cycle of the solar activity and to spread them throughout North-Caspian region.

One may single out indiction (1833–2007). It consists of two century cycles (1833–1923 and 1924–2007) and eight 22-year ones. The duration of the cycle is 175 years (by Bonov).

Every century cycle consists of eight 11-year ones. The duration of the first one is 91 years, the second one – 84.

Peculiarities of temperature regime of the solar activity cycles (Table 1) are:

– medium atmospheric temperature of the even 11-year cycle is colder thah that of an odd one. Together they comprise a 22-year Hoil cycle, in the average the difference is 0,5 degrees;

– medium temperature of the cold season (November-March) of the even cycle is colder than that of an odd one, the difference is about 0,9 degrees;

– medium atmospheric temperature in March of the even cycle (0,8 degrees difference), February (1,7 degrees difference), December (1,1 degrees difference) is colder than that of corresponding temperatures of the odd cycle;

– medium atmospheric temperature of the period of solar activity fall of the even 11-year cycle is colder than that of an odd one (the average difference is 1,0 degrees)

– the lowest temperature during the century cycle of the solar activity has the first and the third 11-year cycles; from the fifth to the eighth 11-year cycles the atmospheric temperature increases;

– medium temperatures of 22-year cycles increase from the first to the fourth (in the century cycle);

– medium temperature of the even and odd 11-year cycles, in the century cycle, increase from the first to the fourth;

– the biggest growth of atmospheric temperatures is in the first and the fourth of the 22-year cycles (0,6 degrees).

On the whole, during the century cycle of the solar activity (80–90 years) the temperature regime develops in the following way: the decrease in the temperature during the first and the third 11-year cycles is lower than the norm (9,6 degrees Celsius). From the fifth to the eighth 11-year cycles the increase in the temperature is above the norm.

The temperature regime differs drastically at different stages of the 11-year cycles. At the stage of the solar activity fall there are about 70 per cent of extremely cold and warm years (winter seasons). The repetition of the cold years is 3 times more frequent in even 11-year cycles. The repetition of the warm years (winter seasons) is 2 times more frequent in the odd 11-year cycles.

Table 1

Distribution of average atmospheric temperatures according to the cycles of solar

11-year cycle		Average atmospheric temperature, C°														
№ of cycle	Duration	XI	XII	I	II	III	Cold season	IV	V	VI	VII	VIII	IX	Warm season	Cold season	Year
8, 9	XI.1833-VI.1843	3,6,	–5,2	–8,1	–5,7	–1,2	–3,2	8,7	16,9	22,7	25,3	21,2	17,4	21,5	10,1	9,0
	VII.1843-IX.1855	3,4,	–3,4	–7,2	–4,4	0,4	–2,6	9,3	18,0	22,5	25,0	23,1	17,2	21,7	10,6	9,6
10, 11	XII.1855-II.1867	2,5	–4,2	–6,2	–7,4	–0,5	–3,4	9,2	17,5	23,0	25,9	21,3	17,8	21,5	9,1	9,0
	III.1867-XI.1878	4,4	–2,7	–6,8	–6,7	0,2	–2,3	9,8	17,4	22,4	24,9	23,7	17,6	21,2	10,4	9,5
12, 13	XII.1878-II.1890	2,7	–1,9	–6,6	–6,5	0,1	–2,6	8,4	18,3	22,7	25,6	23,2	16,3	21,1	9,6	9,2
	III.1890-XII.1901	1,3	–3,7	–6,4	–5,0	0,5	–2,5	9,2	18,2	23,3	25,7	21,7	16,0	21,6	9,9	9,5
14, 15	I.1902-VII.1913	2,8	–2,9	–6,3	–5,3	–0,1	–2,5	9,3	18,1	23,3	25,7	23,5	17,0	21,6	9,4	9,4
	VIII.1913-VII.1923	1,7	–1,8	–2,8	–4,0	0,6	–1,0	10,8	18,1	23,0	25,6	23,2	16,7	21,3	9,2	10,0
16, 17	VIII.1923-VIII.1933	2,2	–3,4	–7,1	–8,3	–0,7	–3,5	9,4	17,7	22,7	25,0	23,3	17,3	21,2	10,0	9,1
	IX.1933-I.1944	2,5	–3,4	–7,5	–5,4	–0,2	–2,9	10,1	17,8	22,7	26,0	24,2	17,6	21,7	9,9	9,5
18, 19	II.1944-III.1954	1,5	–4,4	–7,3	–6,3	0,3	–3,4	10,2	18,2	23,4	25,3	24,0	17,4	21,6	8,6	9,4
	IV.1954-IX.1964	1,6	–2,8	–4,4	–4,0	0,2	–1,9	10,2	18,5	23,7	25,6	23,4	17,0	21,6	10,1	10,0
20, 21	X.1964-V.1976	3,8	–1,9	–6,5	–5,8	0,7	–1,9	11,1	18,6	22,8	25,0	23,4	17,3	21,4	9,8	9,9
	VI.1976-VIII.1986	3,4	–1,7	–4,9	–5,0	1,7	1,2	11,6	18,3	22,2	25,1	23,5	17,5	21,3	8,4	10,0
22, 23	IX.1986-VII.1996	2,3	–2,6	–3,8	–4,4	1,9	–1,3	11,5	17,5	23,1	25,2	23,0	17,6	21,2	10,0	10,2
	VIII.1996 -	3,1	–2,4	–3,1	–1,0	3,7	0,1	11,2	17,1	22,9	25,6	24,2	17,6	21,5	10,6	10,8
Norm	1836–2005	2,8	–3,0	–5,9	–5,3	0,4	–2,3	10,0	17,9	22,9	25,4	23,6	17,3	21,4	9,7	9,6

Average atmospheric temperature of 11-year cycles, °C.

№ of the cycle	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Temperature, °C	8,8	9,5	9,0	9,5	9,3	9,4	9,5	10,0	9.0	9.5	9.2	9.9	9.9	10.0	10.1	10.8
Hoil's cycle	9,15		9,25		9,35		9,75		9,25		9,55		9,95		10,45	

The new, the 24th even 11-year cycle of the solar activity began in the middle of 2007 and will continue till the middle of 2017 (the forecast). The total duration of the cycle will be 10,8 ± 0,7 years. The basic maximum of the solar activity was in the first half of 2011. The maximums of 5–6 year cycles were expected at the end of 2009 – the beginning 2010 and in the period between 2014 and the beginning of 2015.

Typical for even 11-year cycles decrease in the atmospheric pressure in the polar areas during the periods of increasing solar activity will force to move the arctic anticyclone to the north-east. Atlantic cyclones, formed in the humid sea air, will be northerner than usual, which will cause tge decrease in the amount of precipitations in the Volga and the Kama.

In the north-Caspian region anticyclone feature of the climate will increase under the influence of Azorsky and Siberian anticyclones. The weather will be dryer. The amount of precipitations will decrease, especially during autumn-winter season and in spring. Continental arctic air mass, where Siberian anticyclone is formed, will lead a sharp fall in the temperature as a result of intensive radiation cooling.

Intensification of the meridianal form of circulation of the atmosphere during the periods of maximum solar activity will lead to a bigger fall in the atmospheric temperature during autumn-winter period because of artic air intrusion.

The average year atmospheric temperature in the 24-year cycle will be about 9 degrees Celsius which is 0,6 degrees lower than a many-year norm and 1,8 degrees Celsius lower than in the 23 cycle (1996–2007). The fall in the average year temperature will be because of a sharp temperature decrease of the cold season (November-March) till minus 3,0–3,5 degrees Celsius which is 0,7–1,2 degrees Celsius lower the norm and 3,0–3,5 degrees Celsius lower, 1996–2007.

Thus, for 11 years (2007–2017) in Astrakhan region and in the water area of the North Caspian region we should expect dry, with cold winters and strong eastern winds, weather. The total decrease in the quality of the precipitations in the Volga and the Kama rivers will result in the lowering of the Caspian sea level . The winter duration instead of usual 80–100 days (during the last 20 years) will increase to 100–120, and even 120–140 days. Taking into consideration the forecast of the solar activity of the 24th cycle and the peculiarities of the temperature regime of the even 11-year cycle we can suppose that winter seasons of 2008\2009, 2009\2010, 2010\2011, 2012\2013, 2013\2014, 2015\2016 will be colder than the norm. The winter seasons of 2008\2009, 2012\2013, 2013\2014 will be very severe (for about 4,5–5 months).

WINTER TYPIFICATION ACCORDING TO THE DEGREE OF SEVERITY

For the lower Volga and the North Caspian region there are several variants of winter typification according to the degree of severity. Different characteristics were used: the area of the ice cover, the thickness or the volume of the ice; the totsl number of the freezing days, both for one point and for throughout the water area.

The most objective and available one, in terms of getting acute information, is the characteristics of the severity of winters, offered by Tyutnev (1975) for the North Caspian region (Table 2).

Table 2

very severe winter	severe winter	temperate winter	mild winter	very mild
more than 900	900–700	700–400	400–100	less 100

The repetition of very severe and severe winters was counted during the period of 1924–2006. There were registered 8 very severe winters (10 %), 9 severe (11 %) and 65 – the rest of them (79 %). So, the repetition of very severe winters was once every 10 years, severe – once every five years (Buharitsin, 1984, 1994, 2004).

Essential changes of the climatic processes in the lower Volga and the Caspian Sea have occurred during the last years. They influenced the repetition of very severe winters. Last time very severe winter was in 1968–1969. During the following 37 years there were no very severe or severe winters.

THE ICE THICKNESS

The maximum thickness of the ice of the natural growth in the North Caspian region is observed in January – February, and even during very severe winters it is no more than 60 cm in the north-western part and 90 cm in the north-east (Table 3).

Table 3

The absolute maximums of the ice thickness in the delta of the Volga and the North Caspian Sea, centimeters

Point	December			January			February			March	
	1 ten days	2 ten days	3 ten days	1 ten days	2 ten days	3 ten days	1 ten days	2 ten days	3 ten days	1 ten days	2 ten days
Astrakhan	32	42	46	49	47	52	60	64	64	62	60
Ikryanoe	19	37	40	41	44	55	66	71	71	67	63
Olya	19	27	29	32	35	45	52	55	55	46	35
Iskustvennyi ostrov	15	20	21	28	38	49	52	55	55	47	36
Tulenyi ostrov	20	20	20	20	40	45	50	52	50	50	43
Chistaya Banka	17	22	26	28	42	56	69	70	68	67	59
Ukatnyi ostrov	28	36	43	46	47	53	53	54	56	60	60
Shalyga	35	47	58	61	64	64	64	64	70	74	72
Peshnoi	35	41	60	75	64	72	75	78	75	70	69
Zhilaya kosa	25	45	60	66	70	73	83	86	88	90	89
Kylaly ostrov	16	23	26	29	34	46	46	55	56	57	54

CONCLUSION

Such essential forecast changes in hydrological and climatic, certainly, will tell badly on all, without any exceptions, economy branches, and not only of Astrakhan, Astrakhan region, but the whole north-Caspian region. It will result in additional expenditure both in warm, and in cold seasons of the investigated period. The increase in the continental character of the regional climate will affect agriculture, water transport, and fishing industry. It will be necessary to conduct additional dredging, reclamation operations, and, possibly, reconstruct many existing coastal sea and river hydrotechnic constructions and objects. There will be rapid increase in housing and public utilities costs on water delivery, especially in summer-autumn drought periods, as well as, on heating of accommodations, service and industrial buildings in cold seasons. Consumption of electrical and heating energy and of various types of fuel will grow considerably.

Lowering of the Caspian Sea level primarily will affect its shallow Northern part. In warm summer seasons it leads to intensive heat penetration and water evaporation from vast shallow waters of North Caspian, increase of sea water salinity up to hazardous levels, rise of hypoxia vast zones. In cold seasons, in the result of shallow waters low thermal capacity under the influence of low temperature and intensive wave overturn in the initial period of ice formation, strong ice cover will appear at North Caspian, whose thickness reaches its maximum long-standing values in the middle of winter.

In view of the fall of the Caspian Sea level and decrease in the depth of shallow north part of the sea, the intensity of hummocking ice processes will sharply increase. Particular risk will be in the form of floating packed ice brought by wind and streams into the deep-water middle part of the sea and drifting along the shores to the south. The sea bottom, practically all over the territory of the North Caspian, will be subjected to exaration by heavy drifting ice. The frequency and intensity of dangerous set-downs will increase, which will lead to massive fish mortality, especially in winter months under ice and in spring during its concentration during spawning season.

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THE NEW INTEGRATED DIRECTION TO THE STUDY OF DANGEROUS NATURAL PROCESSES OF GLOBAL CLIMATE CHANGE

ABSTRACT

The article explores ways to address climate change as a dangerous natural process. Today, the global development of science is presented as a system consisting of a set of interrelated components of civilization and nature. Climate is a limiting factor in the extreme conditions of human life. The development of thermodynamic theory of irreversible processes, theory of nonlinear dynamical systems has led to a qualitatively new understanding of natural phenomena. The notion of climate as an open dynamic nonlinear nonequilibrium systems – a new approach to the study of natural hazard processes.

INTRODUCTION

The risk of being increasing in view of the law-governed social contradictions and extremes of natural processes is a distinctive feature of human existence at this time. Climatic anomalies – floods, heavy snowfalls, landslides, droughts, earthquakes and tsunamis are considered as sudden natural disasters. Their manifestations, as well as global climate change, trying to explain the growing negative impact of man on nature, extensive technological development. Classical science in its state of crisis can not detect other causes occurring in the nature of the processes. The true meaning of what is happening effectively veiled by the laws of the financial world. An example is the emergence of the Kyoto Protocol, with the idea of "global warming", ahead of the scientific basis of this issue. The international community so concerned about global warming, which decided to limit emissions of greenhouse gases in the atmosphere, so "cool" the planet. But one can hardly expect the effectiveness of these measures, if we do not even know the nature of what is happening. In a fundamental report by the Intergovernmental Panel on Climate Change was formulated conclusion as the results of current research climate can not be regarded as conclusive evidence of a clear causal link between anthropogenic impacts and changes in surface temperature on Earth. At this time, the media create a negative pressure informational messages about the imminent onset of the Apocalypse. Uncontrolled, unconscious "psychologisation" people's consciousness, causing mass hysteria, can dramatically change the reality and lead to serious violations of the natural ecological balance on Earth. How destructive geological force, it slows down the process of evolution of the biosphere into the noosphere [4]. Modern science has become a synergistic symbiosis industry knowledge, industry and industry somputing superhightech. Human activities have already reached the deepest level of the fundamental structure of matter – quark level. Strategy kollaydinga hadronic matter, beginning with the Large Hadron Collider, could serve as the launch of avalanche processes in the surrounding natural world. That is why research into the causes of dangerous natural processes, which include global climate change requires a new integrative scientific thinking, the spiritual world view [1–5, 10, 13].

In recent decades, science rapidly, outstripping the ability of human awareness of what is happening, and develop a global view of evolution. The development of thermodynamic theory of irreversible processes, theory of nonlinear dynamic systems with a synergistic approach has shown limited single-valued "linear" representations of the world. Rationale compatibility second law of thermodynamics of open systems with the ability to self-organization – one of the greatest achievements of modern physics. Prigogin [10] contrasted the patterns of development closed systems open the unstable non-equilibrium systems for which a small input signal can give a strong response is unpredictable at the output. At a crucial turning point in the bifurcation point, it is impossible to predict which path the further development: whether the system state or random move to a new level of order, as a result of self-organization. For complicated natural systems characterized by properties described only by means of nonlinear models for which the unnatural limitations of solutions characterized by the vibrational modes and multistatsionarnye. Natural science has concluded that the ambiguity and instability of the initial conditions is the natural state of natural systems.

Kapitsa and Kurdyumov [6] proposed a mathematical model of a modern state in the form of evolutionary mode "blow" explosively situation, leading to a collapse with unpredictable consequences. One of the main problems of modern nonlinear dynamics is to develop methods for studying such systems, the conditions for ordering. Without knowledge of the evolution of the physical mechanisms of the formation of weather and climate can not predetermine the future course of events in the process of climate change. A key principle of scientific forecasting methodology is the principle of "selforganized criticality", which is the main feature of nonlinear systems, the evolving state of near chaos is the ability to respond to internal fluctuations are not only destructive but also creative avalanche process. The phenomenon of "self-organized criticality" reveals itself in various forms: self-organizing systems at the edge of the supercomplex of chaos in the occurrence of turbulence in the fluid, avalanches, earthquakes, nuclear and chemical chain reactions, the dynamics of the plasma, lasers, social and scientific revolutions, and others. The conclusion from the theory of self-organized criticality is that the elimination of one of the dangers of possible bifurcation points, often increases the likelihood of other undesirable options. On the other hand, small, well-localized crises, such as hazardous to human nature's processes, can defuse the growing tension in the system and thus prevent or delay the onset of major crises [6].

Hazardous natural processes are the object of scientific research geo-environmental. In the last two decades has been a significant update of geo-ecological paradigm. Geoecology evolved into a powerful integrative research field with an independent interdisciplinary approach to the study of complex natural systems of Earth, as a habitat for humanity, in a spontaneous mode of development and under anthropogenic stress. Geoecological culture of personality, accepting as a basis of an outstanding scientist heritage Vernadsky (1863–1945) [4], helps to form a new human world view, which is to go beyond the usual thinking. Changes in the relationship of man and nature both coevolution leads to changes in the environment and the social activities of man.

Global ecosystem is a unified whole in which nothing can be won or lost, all that was recovered by man, should be returned. Payment on this promissory note can not be avoided. It can only be postponed. That is the law of independence of the biosphere. Secure their future at a new stage of evolution of the planet's people will be able only if the will be responsible for maintaining the integrity of the biosphere, if spiritually reborn. Processes of evolution of the biosphere to the noosphere will run – mind geoenvironmental cultural rights. The material interests of mankind must be subject to moral and ethical laws – a necessary change, which should happen in the emergent human consciousness.

Climate can be regarded as an open non-equilibrium natural system, which continually fluctuates, defining the extremity of the human condition. After passing through the bifurcation point, it will not return to its original state, but will have completely different characteristics than those who were previously. This is a threat to humanity. After all, people optimally corresponds to the climate in which it originated. To date have, there are several points of view on the issue of global climate change. One group of researchers [3, 7] believe that since the end of the Holocene optimum, all five thousand large variations in climate are not exhibited. The observed changes are local in nature and are the result of economic activity, neotectonic processes, volcanism. Researchers at the second direction [7, 8] are of the opinion that there interdecadal climate variability and age-old with a periodicity of 3–4, 7–11, 35–45, 70–90 years old. The third area is the concept of centuries of climate variability and the overall moisture content of the continents of the Northern Hemisphere with a period of 1800–2000 years – supporting research Shnitnikova [1, 2, 7, 12].

Naydenov [9] mathematically concluded that the physical mechanism of climate variability is that the rate of accumulation of moisture due to precipitation of land exceeds the rate of decrease due to river runoff, and increase moisture causes a decrease in land albedo of the Earth. The positive feedback of these phenomena leads to the instability of the climate. Essentially, this means that the Earth is constantly supercooled through glacial periods, climate cooling or warming through overheating and moisture Climate mode "wet and green" earth. Instability of the Earth's climate occurs when the planetary albedo and evaporation decrease with increasing humidity, and precipitation increases with increasing temperature. Other thermal feedback can only reduce the critical threshold of instability, but does not abolish it. Stabilization of the instability is possible due to the feedback, for example, growth and evaporation increase river flow reduces the moisture content in the soil and prevent decrease of the albedo. According to this concept of modern warming is the cause of progressive change in Earth's heat balance due to the accumulation of water on land. Climatic variability is a mixture of deterministic signals, due to linear and nonlinear responses arising from spontaneous transitions between different states of the climate system. Empirical knowledge of past climates do not favor the greenhouse disaster. Earth's climate system constantly moves from one state to another, and a stable equilibrium for it is more the exception than the rule [9]. The complexity of studying the climate and environmental issues emphasized by the fact that it includes the volatile and vulnerable "living substance" of the biosphere Earth. Self-organization of the world leads to the appearance of new emergent natural processes that humanity will inevitably have to face when moving to new stages of evolution. This is the result of development. Evolution may be accompanied by an uncontrolled dynamics through the "chaos" of dangerous natural processes [10].

All of the physical processes of self-organizing system of the Earth should be viewed as the result of its impact on the atmosphere, lithosphere, hydrosphere, cryosphere periodically changing external influences, consisting of cosmogenic factors: movement of planets in the solar system, Earth's satellite – the Moon and the Sun. The direct impact on the biosphere, space clearly and convincingly shown at the level of individuals of distinguished scientist Chizhevsky [11], the development of ethnic groups scientist Gumilev [5]. The author of this article investigated the dependence of natural hazard events and man-made disasters in the Caspian Sea to changes in solar activity. Graphic shows the result of increased dangers as a response to "selforganizing criticality" geo-ecosystem Sea at the beginning of a process of intensive development of hydrocarbons. Not homogeneous and self-organizing feedback system of the Earth, including the biosphere, the external cosmic impact. For these reasons, climatic as well as other natural and biospheric cycles vary in duration and strength of expression. They are superimposed on one another, have no clear time limits and develop in the mode of oscillation. Geo integrative approach to studying the Earth's climate system says about the protracted process of bifurcation, "global warming" in the coming decades may be replaced by a global "cooling" [1–3, 7, 9].

CONCLUSIONS

Nature has challenged mankind. What would be the answer depends on whether the person to concentrate his mind on the nature of the search set of the problem. This is the condition of the highest spiritual stage of its evolution. That is why the progressive-minded scholars are aware that humanity, if it wants to preserve civilization, should solve environmental problems in the coming decade, otherwise damage becomes irreversible biosphere processes.

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THE ROLE OF DRIFTING ICE IN BUILDING THE BOTTOM LANDSCAPE AND SEDIMENT COMPOSITION IN THE SHALLOW WATERS OF NORTH CASPIAN SEA [7]

ABSTRACT

Shifts and the ice drift in the shallow northern part of the Caspian Sea can have a significant impact on economic activities. The revitalization of the oil companies in Russia and Kazakhstan, with its foreign partners for exploration of hydrocarbons in the North Caspian shelf, requires serious scientific, environmental and technical support of these activities. In this paper we present the results of joint research in ice. The predominant type of modern sediments in the northern Caspian Sea is silt (sandy mud, mud). Thick deposits of soft mud in a river are areas that form sediments of rivers. In all soils there is an admixture of broken and whole shells, and in some areas it is the main part of the bottom sediments. It is represented by the following forms: Cardium edule, Didacna trigonoides, Didacna barbot-de-marnyi, Adacna plicata, Monodacna edentula, Dreissensia polymorpha, Dreissensia distincta, Theodoxus pallasi, Zagrabica brusiaiana, Caspiella eichwaldi (Figure 1). On the surface sediments are more enriched with muddy material, which is accumulated by the decomposition of algae dying and Zostera, silty sediments of aeolian origin. According to B.I. Koshechkin (1958), the percentage of coarse fractions in soils (the size of shell fragments is more than 1 mm) from 6 to 19,2 %. In some areas at the bottom of a small (less than 10 cm) layer of recent sediments lies an ancient breed – khvalynskaya clay. Numerous underwater banks and some islands of the Caspian Sea (for example, Little Pearl Island) consist almost entirely of whole and broken shells.

It is believed that the main cause of the destruction of the dead shells of mollusks is the sea swell. However, due to extreme shallow marine delta of the Volga region and the entire eastern part of the North Caspian, the storm does not develop a strong emotion. The frequency of wave height of 0,5 m is 58,6 % [3]. The maximum wave height is no more than 1,0 m This is clearly not enough for rather solid shells Didacna trigonoides or Didacna barbot-de-marnyi to be crushed. Rather, they will slowly fray and eventually become thinner, such as it occurs in the surf zone of Dagestan coast.

[7] The role of drifting ice in building the bottom landscape and sediment composition in the shallow waters of north Caspian Sea / Buharitsin P., Ayazbayev E. // ISSN 0376-6756. Material of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions (June 9–13, 2013, Espoo, Finland). Finland, Helsinki 2013.

Figure 1. Shell fragments entirely predominate in these soil samples

In our opinion, the main cause of mechanical damage to shells is drifting ice. For the first time the impact of drifting ice in the bottom of shallow waters of the North Caspian was studied and described in the works of the Laboratory of aerial methods AS of the USSR [2]. In subsequent years, this work has been continued. The studies found that gauging furrows present long, often straight furrow with the length from a few tens of meters to several kilometers. The furrows are formed under the influence of hummocky pack ice the bottom. They are oriented in the direction of prevailing during these periods eastern, south-eastern and north-westerly winds and present vectors of ice drift, drawn along the bottom (Figure 2).

Furrow width varies from a few up to 50–100 m and over. There are grooves, gradually widening in the direction of ice movement. Some are crooked or broken lines, indicating a gradual or sudden change in direction of the drift ice. All furrows end with shafts, that are formed with furrowed ground. The height of some of them is more than the depth of the sea, and they come to the surface in the form of small islands. Bright gauging furrows on the darker bottom background can be visible from the plane. A large number of furrows is observed in spring, after clearing rom the ice, when the water is not puddle with spring storms, in the area of Chapurenok, Chistaya Banka islands, Seal Isles Archipelago as well as in the shallow waters of the northern and eastern coasts, where their density reaches 20–50, and sometimes 100 or more furrows at 1 km route. The timeline of furrows in the muddy soils comprises 2–3 years. In sand furrows are smeared with seaways in a single season (Figure 3).

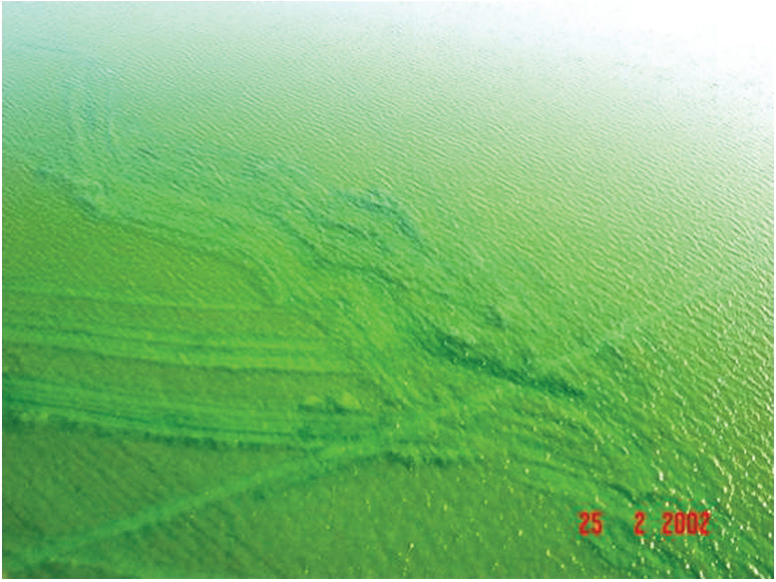

Figure 2. Gauging furrows on the bottom of the North Caspian. The view from the helicopter

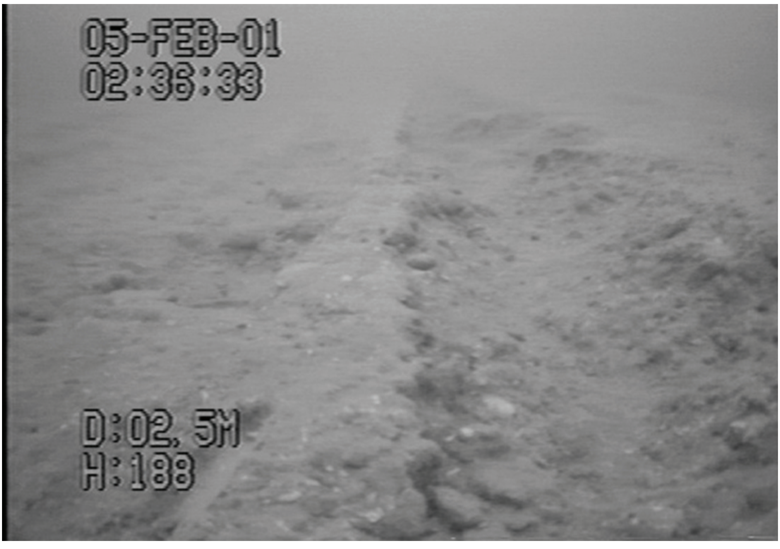

Figure 3. Typical gauging furrows on the bottom of the North Caspian Sea. Underwater picture

The ploughing effect of drifting ice is also characteristic of the coastal zone. Drifting ice from the sea, arriving on shore, plow topsoil out, leaving traces of ploughing with the depth of 0,5 m and length of several kilometers. On the islands of the North Caspian during heavy ice drift along the coast strong piles of ice are formed. Fragments of ice, thus penetrating into the soil to a depth of 1 m, retain up to the end of May. There has been a case, when the wellhead in the Volga seaside on an island a house has been moved from the basement with the drifting ice.

When landing ridges on the ground there is further accumulation of ice as a result of ridging under the influence of movement and drift. As a result, hummocks can penetrate into the soil to a depth of several meters. The depth of their penetration into the soil depends on physical properties of soil, hummock mass, contact area and the depth of the sea.

More than 50 % of the Northern Caspian is subject to ice ploughing (pack ice interaction with the seabed). These processes are of massive (albeit seasonal) nature, and therefore play an important role in the ecology of the Caspian Sea. Due to mechanical impact of drifting ice, there is not only movement of huge amount of bottom soil. At the same time shells if dead clams are damaged on the bottom [1].

As a result of intense ice movements, there are cases of destruction and loss of pressurization of plugged exploratory wells in the offshore eastern (Kazakh) sector of the North Caspian Sea. A large number of these wells were on the sea coast, but were flooded during the rise of the Caspian Sea (1976–1996).

Figure 4. Typical Caspian "winter" grounded ice

Similar processes occur in Russian sector of the North Caspian Sea. Production and environmental monitoring, which the Russian company Lukoil has carried out for many years over muted exploration wells, which are located in the license areas of the bottom at a depth of 6 to 28 meters, has not revealed significant changes. However, the concrete cap of the well, located at a depth of 6 m, was partially damaged, which suggests the effect of drifting ice on it. In addition, around the well, the divers observed broken shells, which were not found near the other wells, located on the bottom in deep water.

Toroses and hammocks formed can easily force in or break through underwater facilities located on the bottom or at inadequate sea bottom. The result is catastrophical consequences for the Caspian Sea ecosystem (Figure 4). In the last two decades in the North Caspian there has been intense work on the development of the local hydrocarbons, accompanied by the design and construction of fixed platforms, subsea pipelines and other oil and gas infrastructure. Therefore, the evaluation of the intensity of ice impacts related to hazardous natural processes is a key element to ensure geotechnical safety of oil and gas facilities and environmental security in the area.

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USE OF SATELLITE DATA IN MAPPING NORTHERN CASPIAN ICE COVER[8]

The rapid development of space technology in the 1970s in Russia resulted in fundamentally new and promising methods for the study of the hydrological regime of seas and oceans, including the assessment of sea ice status and dynamics. Launching specialized artificial satellites (AS) and creating the network of autonomous satellite information receiver stations (ASIRS) contributed to this. In 1975, such a receiver station was created on the basis of Astrakhan Zonal Hydrometeorological Observatory (AZHO). The first TV images of the Caspian Sea ice cover were received from NOAA satellite in winter 1976. They were used to verify the position of ice boundaries and edges acquired by visual aerial ice reconnaissance. A simple and rapid method was proposed for making ice maps based on ASIRS data, and that gave a start to the regular study of the Caspian ice using satellite information.

A characteristic feature of the hydrological conditions in the north of the Caspian Sea is the formation of quite a stable ice cover in cold season. Depending on winter severity ice remains from 1,5 to 5 months a year. Ice affects maritime industries significantly. Ice cover information scope and quality requirements increase each year. This became especially important in connection with the expansion of hydrocarbons exploration and production in the freezing waters of the sea. We began using satellite ice cover data in the field-work in 1975, upon commissioning Astrakhan autonomous satellite information receiver station. The advantages and disadvantages of conventional (aerial and ground) techniques of the Caspian Sea ice cover imaging were considered. The first attempt was made for the regular use of Meteor and NOAA satellite TV images in the ice maps preparation to better meet a marine industry need for providing a prompt service, and for scientific purposes.

This revealed new possibilities offered by satellite information in the study of sea ice when it is used together with the data obtained by traditional imaging techniques. A graphic-optical technique for transforming the Northern Caspian ice cover images made by Meteor and NOAA into ice maps (rationalization proposal № 54 (1439) of 01.08.1980) was used in the field work for the first time in the Caspian Sea in 1978.

The proposed method will significantly speed up the process of receiving and processing satellite data (a very important factor in the field work), as well as improve the informativity of ice maps produced during satellite TV images decoding by performing imaging synchronous and quasi-synchronous with air reconnaissance [1].

[8] Use of satellite data in mapping northern Caspian ice cover / Buharicin P.I., E.Kh. Ayazbayev // Материалы 22nd IAHR International Symposium on Ice, 11–15 August 2014, Singapore. (электронный вариант, на флэш-карте). – P. 119-126.

Comparative accuracy analysis of ice maps produced using Meteor satellite TV images with synchronous ice aerial reconnaissance showed satisfactory matching of the fast ice boundaries, drifting pack-ice edges, and the size and position of flaw polynyas, equal to an average of 3–5 miles. Moreover, satellite data receiving and processing takes a minimum of 20–30 minutes, which greatly improves ice maps efficiency and quality. This allows satellite information to be used as primary information for flight training, for the approval of regular ice reconnaissance routes by aircraft crews, for updating and refining the ice situation in those areas of the sea where ice reconnaissance was not available for whatever reasons, as well as for operational support of marine industry and scientific purposes (Buharitsin, 1983, 1984, 1987).

Thanks to satellite data we were able to trace the origins and development of flaw polynyas – an important element of the winter and changing hydrological conditions. Ice aerial reconnaissance did not give such an opportunity due to lack of observation frequency and data completeness [2].

Polynya positions and their development processes are determined by speed, direction and duration of wind effect, as well as under-ice currents speed and direction. Using satellite data helped in finding that polynyas in the Northern Caspian develop from hundreds of meters wide and 10 miles long and more and sometimes up to 100 miles long or more due to stable and strong off shore winds between fast ice and drift ice. Surface drift currents resulting from wind influence on the ice-free sea surface contribute to such giant polynyas formation. Ice conditions can change very quickly when the wind alters. Drift ice covers existing polynyas, and creates new ones on the windward side at the same time.

Extensive flaw polynyas imaged by the satellite during 1980s-90s put on a generalised map made it possible to determine the areas of the North Caspian Sea where fast ice is stable, i.e. sea areas where fast ice remains throughout the entire ice period from its formation until ice fracturing in spring.

It was found that fast ice boundaries movement to the south does not occur gradually during the formation of ice, as was previously believed, but irregularly by tens of miles at once, as drift ice consolidates under the influence of wind and its subsequent freezing. The boundary between the older and newer fast ice are often clearly marked as kilometres of hummocky ice ridges similar to those which are formed in the Arctic seas drift divides. They are clearly visible on satellite images and easily deciphered.

During aerial ice reconnaissance in midwinter, observers often noted the presence of polynyas in those sea areas where fast ice was expected to be found. Attempts to explain this by the presence of only the dynamic factors (subglacial currents, ice drift) had not been confirmed.

Information about such polynyas has been accumulating with the appearance of satellites.

Analysis of accumulated aerial and space data resulted in a conclusion that some polynyas are formed annually in the same places. S.A. Brusilovsky (1986) suggested that polynya locations are related to salt domes present in the Northern Caspian waters. Further studies confirmed this relationship: recurring polynya locations coincide with salt domes cropout on the North Caspian Sea bottom [2].

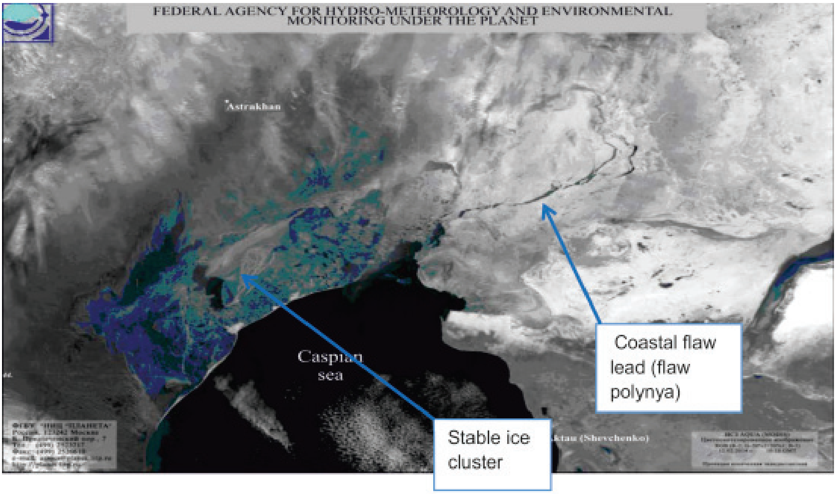

Figure 1. AQUA (MODIS) image of the Northern Caspian waters with highlighted characteristic elements of the ice cover

It has become possible to trace daily incremental ice distribution variations throughout the Northern Caspian thanks to the compatible aerial and satellite data, which could not be done using traditional methods of the past, including aviation. The findings are as follows:

– Drift ice in Guriyev Borozdina ("hollow") does not enter the shallow Buzachi threshold in the western part of the sea even during intensive westward drift at the periods of lowstand at minus 29,0–28,5 m.abs. levels. Ice drift is limited by the physical dimensions of Guriyev Borozdina.

– Ice fractures and flaw polynyas appearance and positions depend on wind direction, speed and duration (Figure 1);

– There is stable ice cluster that forms between the islands of Chistaya Banka and Little Pearl every year, and preserved there during the winter season;

– The sequence of fast ice break processes in spring was traced;

– The possibility of detecting and identifying polluted ice boundaries was confirmed;

– The possibility to detect and determine the extent of spring ice blockages in the marine part of the Volga-Caspian canal.

Weather (mainly cloudy) affects satellite data quality and quantity significantly. Clouds reduce ice maps informativity drastically, and heavy clouds (7–10 score points) make using satellite TV imagery data completely impossible. The informativity of ice maps created using satellite imaging makes up 20–70 % (average of 50 %) of aerial ice reconnaissance informativity, which is taken as 100 %.

Satellite ice information has been received, interpreted and used for operational and scientific purposes according to the guidelines (Buharitsin, 1981) since the winter of 1978–1979. In subsequent years, ice cover data for the Northern Caspian has been received and processed by AARI, the Unified National Ocean Status Information System (UNOSIS) and other organizations, including foreign ones, on a regular basis. Aerial ice reconnaissance in the Northern Caspian has ceased almost completely in recent years, and satellite data have been the only source of information on Caspian ice distribution and dynamics. An electronic archive of the Northern Caspian ice maps was created as a result of long-term ice research [3].

Analysis of strategic ice maps compiled by UNOSIS and AARI in winter season 2013 using satellite data showed high reliability and accuracy of ice cover characteristics such as the position of fast ice and floating ice boundaries, flaw polynyas and leads, compacted and open-pack ice zones, drift ice closeness and ice floe dimensions, and snow-covered ice (Figure 2). However, one of the most important features, i.e. thermally accumulated ice thickness indicated on ice maps with respective symbols, does not correspond to the actual measured in-situ ice thickness. Thus, the results of numerous actual instrumental measurements of fast and floating ice thickness in the eastern part of the North Caspian made by the authors during the period from 6 to 15 February 2013 showed that minimum flat ice thickness was 45 cm, and the maximum made up 90 cm (corresponding to thin and medium size white ice classes) (Table 1).

Table 1

Thermally Accumulated Ice Measured Thickness

Observation date	Measurement point No.	Coordinates	Sea depth, m	Measured ice thickness, cm	Remarks
1	2	3	4	5	6
06.02.2013	1.	N 46° 12′ 00″; E 50° 34′ 02″	4,0	45–53	Measured dimensions of ice floes in hummocks (cm): 30×60; 80×120; 150×200. Individual floes reach the size of 2×4 m. Ice floe thicknesses ranging from 45 to 53 cm
	2.	N 46° 12′ 00″; E 51° 00′ 00″.	6,5	40	Floating ice
08.02.2013	3.	N 45° 52′ 30″; E 51° 00′ 00″	9,0	41	Floating ice

Continuation of the Table 1

1	2	3	4	5	6
08.02.2013	4.	N 45° 52′ 20″; E 50° 45′ 10″	3,5	45	Floating ice
	5.	N 45° 59′ 59″; E 51° 41′ 74″	7,9	45–90	Point № 5 is in close proximity to the giant ring stamukha formed presumably in late December-early January. Its extends for about 300 m. Height of the most prominent peaks of the stamukha had been measured by a helicopter altimeter: 10 m, 13 m, and 15 m. The highest instrumentally measured peak reaches 17 meters. The stamukha incorporates ice floes of different sizes, from 30×30 cm to 100×150 cm and bigger. Some ice blocks are the size of a small room. Ice thickness varies within a wide range from 45 cm to 90 cm. The most common thickness is 53–60 cm
15.02.2013	6.			54	Shore-fast ice
	7.	N 46° 53′ 79″; E 50° 28′ 95″		53	Fast ice, 5 km from the coast
	8.	N 46° 49′ 35″; E 51° 26′ 836		54	Fast ice, 10 km from the coast
	9.	N 46° 45′ 006; E 51° 22′ 980		45	Fast ice
	10.	N 46° 41′ 133; E 51° 18′ 465		49	Fast ice, 15 km from the coast
16.02.2013	11.	N 46.07.30; E 50.53.30	7,9	47	Floating ice
	12.	N 46.57.60; E 50.47.00	3,6	48	Floating ice
	13.	N 45.57.60; E 50.53.30.	4,0	47	Floating ice
	14.	N 46.02.60; E 50.40.30	5,1	49	Floating ice
	15.	N 46.02.60; E 50.47.00.	5,5	50	Floating ice

The end of the Table 1

1	2	3	4	5	6
16.02.2013	16.	N 46.02.60; E50.53.30	7,05	50	Floating ice
17.02.2014	17.	N 46.10.10; E 50.50.00	5,2	47	A small stamukha nearby the measurement point
	18.	N 46.10.10; E 50.53.30	5,9	49	Floating ice
	19.	N 46.10.10; E 50.57.00	6,0	47	Floating ice
	20.	N 46.07.30; E 50.40.30	4,0	47	Floating ice
	21.	N 46.07.30; E 50.47.00	4,9	53	Floating ice
	22.	N 46.07.30; E 50.57.00	7,0	49	Floating ice
	23.	N 46.00.00; E 50.37.30	5,2	48	Floating ice
	24.	N 45.54.00; E 50.41.10	7,0	49	Floating ice
	25.	N 45.52.30; E 50.37.30	4,0	47	A stamukha nearby the measurement point
	26.	N 45.48.30; E 50.53.30	4,5	45	Hummocks ridge extending from north to south, it stretches for 1,5–2,0 km. The ridge height is 2,0–3,0 metres.
	27.	N 45.45.00; E 50.37.30	4,0	49	Floating ice

According to the same satellite ice maps, ice thickness maximum does not exceed 25–30 cm of gray-white ice (Figure 2) both in the western and eastern part of the sea for the entire cold season.

This suggests that ice thickness estimates made on the basis of satellite images are currently very approximate and do not provide reliable and accurate results, so satellite information must be adjusted and corrected using ground-truth data (terrestrial) observations.

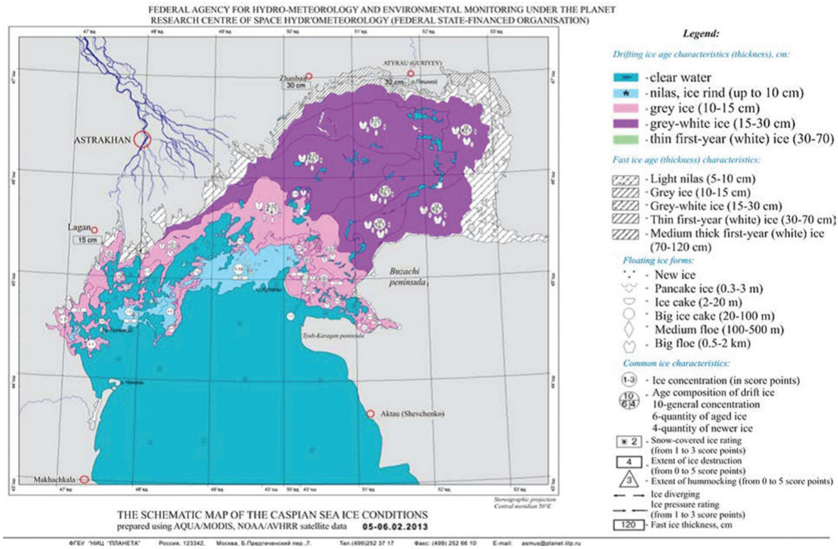

Figure. 2. The schematic map of the Caspian Sea ice conditions prepared in AARI using satellite data

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ROLE OF DRIFTING ICE IN BOTTOM RELIEF FORMATION OF FREEZING SHALLOW WATERS OF THE SOUTH OF EURASIA [9]

ABSTRACT

The results of many years investigations of ice regime of freezing shallow waters of the South of Eurasia (the sea of Azov, the Northern part of the Caspian sea-lake, the Aral sea, lake Balkhash) suggest that, despite significant differences in their hydrological regime, the processes of ice formation and dynamic processes in the ice cover of these waterbodies have similar features. It is established that changes in the ice cover and ice thickness are influenced by the same factors. It enables to predict not only the thickness of the ice, the average ice coverage of these waterbodies, but other, more important characteristics of the ice regime, such as ice movements and ice drift, hummocking, areas of compressions and rarefactions, the formation of stamukhas (grounded ice hummocks), etc. A characteristic feature of the ice regime of all the above mentioned shallow water bodies is the presence of drifting ice in the winter period, intensive movements and hummocking of ice under the influence of external forces (wind, currents), and, as a consequence, the interaction of rafted and hummocked ice with the bottom and banks. These features play an important role in the relief formation of bottom and banks of these water bodies, and refer to the main relief-forming factors. In conditions of intensively growing economic activity, the importance and significance of ice research will steadily increase.

ESTUARINE SEASHORE OF THE VOLGA RIVER AND NORTH CASPIAN

Ice cover in this part of water area appears annually. The average date of the first appearance of ice – December 8. The period between the date of the first appearance of ice and the onset of stable ice formation in severe and moderate winter is 2–3 weeks. In mild winters, sustained ice-building may not be observed during the winter period. Fast ice is settled in severe winters in an average of 10 days, in moderate winters in 20 days after the onset of stable ice formation. In severe and moderate winters, maximum thickness of flat ice (40–50 cm) is registered in the third week of February. Due to intensive movements of the ice caused by strong east and southeast winds, the number of ice layers can reach 8–10, and the thickness of rafted ice can be 1,5–2 m. Sometimes the ice jams up to the bottom. Under the influence

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[9] Role of drifting ice in bottom relief formation of freezing shallow waters of the south of Eurasia / Buharicin.P.I. // ISSN 2414-6331. Material 23RD IAHR International Symposium on Ice, 31 May-03 June 2016, Ann Arbor, Micigan. (США). (электронный вариант, на флэш-карте). – P.1-9.

of the wind and currents, floating ice drift is observed in the freeze-up period on the estuarial seashore of the Volga river and in the shallow northern part of the Caspian Sea. Depending on the resulting direction of movement, the ice drifts:

– along the edge of fast ice (ridged and hummocked ice is formed along the edge, the length of which can reach several kilometers, its width is 10 m or more and the height is 2 m or more. Hummocked ice ridges are usually elongated parallel to the marine edge of the delta);

– from the edge of the fast ice to the open sea (in such cases, coastal flaw leads (polynyas) are formed between the edge of the fast ice and drifting ice massif, the length of which is several tens of kilometers, and their width is hundreds of meters. Sometimes the length of some giant polynyas can reach more than 100 miles and the width – up to 20 miles. In the ice massif, there is a general diverging and decrease of floating ice concentration);

– to the edge of the fast ice, perpendicular to its general strike (in these cases, there is a breaking of the fast ice, its intense movements, and numerous stamukhas are formed at the sea shoal – hummock, standing on the ground. There is the compaction of drifting ice, compression zones are formed inside the ice massif);

– chaotic, messy ice drift, when individual ice fields are moving in the massif each with its own speed and its trajectory (upon that there is an intensive areal rafting and hummocking of ice, the formation of local zones of compression and rarefaction) [1].

Movements of ice fields create zones of compression and rarefaction of ice. High-ratio compression occur due to east and south-east winds with a speed of 12 m/s and more, as well as when it changes from southeast to northwest. This is facilitated by the wind-induced fluctuations of the sea level, the magnitude of which can reach 1,5–2,0 m. In areas of compression, there is an intensive rafting of ice, hummocking and formation of stamukhas – hummocks, standing on the ground. In the areas of rarefaction, polynyas and leads are formed. The rafting of ice occurs in the Caspian sea almost every year as a result of thrusts of one ice plate to the other. Typically, the rafting involves the newly formed ice with thickness less than 30 cm. The maximum thickness of the rafted ice can reach 3 m, and ice hummocking, according to ice aerial reconnaissance, 3–4 balls. The beginning of destruction of the ice sheet after severe winters is observed in the first-third decades of March, after moderate winters in the third week of February, after soft ones – in the first decade of February. Final clearance of ice of the North Caspian in the areas of activity of Russian oil companies after severe winters occurs in the first decade of April, after moderate winters in the second decade of March. The duration of the ice period varies significantly and is 18 – 136 days depending on the specific severity of a winter.

In the North Caspian, there are stamukhas of autumn and winter origin. Stamukhas of the autumn origin are formed in November-December from thin ice of 5–15 cm in thickness. They are usually small sized in diameter and their height is of 1–3 m above the flat ice surface. Such stamukhas are formed throughout the coastal strip to depths of 2 m. Stamukhas of the winter origin are usually formed from gray-white and white ice of 20–70 cm in thickness. They can reach sizes of 100–300, sometimes 500 m in diameter and the height of 10–15 m. The maximum registered height of the stamukha sail was 20 m. The maximum depth, to which the formation of stamukhas on the Caspian Sea was documented, is 12 m [2].

Under equal thermal conditions of ice formation, an important determinant of the intensity of ice- exaration process is the current position of the sea level. Level fluctuations of the Caspian Sea, the amplitude of which was 3,5 m in the twentieth century, in general, have a significant impact on the relief of the shallow water, which largely determines the hummocking of the North Caspian [3]. Considering the uneven distribution of depths, the bottom area exposed to ice-exaration influence is expanding under the transgress conditions. In the context of regression, by contrast, it is sharply reduced.

The first person, who paid attention to the "traces of the activity of moving ice" on the surface of the seabed of the North Caspian and published a pioneering article on this subject, was B. I. Koshechkin [4]. In the production of aerogeological works with application of materials of aerial photography and aerial visual observations within the eastern coast of the Caspian sea, he noticed a specific picture on the surface of the seabed. At the first glance, this pattern is erratical, intercrossing gouges and trenches of light color on the darker bottom surface. Sometimes there are whole series of these gouges that are strictly parallel to each other and having a form of a "comb". Typically, this pattern is confined to shallow areas of the water area, which are covered with ice in winter. It is clear and well-defined the most within the shallow zone of the Mangyshlak Bay, down to the depths, bounded with a 3 m long isobath [4]. Some gouges represent crooked or broken lines, which indicate a gradual or abrupt change of the direction of the ice drift. There are swells on the ends of the gouges formed from the exhausted bottom soil. The height of some of these swells is greater than the depth of the sea, and they appear on the surface in the form of small ephemeral islands. Such islands are usually destroyed after the first spring storm.

The analysis of the distribution of the main directions of trenches and the comparison of these directions with the direction of the prevailing winds showed that the movement of the masses of heaped ice is subject to prevailing winds and currents driven by them. Ceteris paribus, the greatest intensity and depth of exaration of the seabed are confined to the area of drifting ice, drawn to the edge of the fast ice, where hummocking occurs during the whole cold season and along which the drift of ice fields takes place with frozen into them and reaching the bottom hummocky formations. Imbedded in drifting ice fields, and having enormous weight, they create the deepest and most extensive gouges of exaration, which can pose a serious threat to underwater pipelines (Figure 1). The results of data processing of side scan sonar and echograms revealed the presence of clearly expressed gouges and gouge systems in bottom relief, including deep-sea area (depth up to 12 m), formed by the drifting one and multicarinate hummocky formations frozen into the ice fields. On the whole, 238 gouges and systems have been identified on the pipeline route.

The length of the largest and most distinct of the detected gouges, apparently (most of the gouges cross the surveying range and no one knows where they end) exceeds the first kilometers; the width of single gouges – up to 5 m, systems of gouges – up to 200 m. The exact depth of the gouges, due to the constant churning of water could not be determined, but, according to side scan sonar and echo sounders, it is up to 1 m. In addition to linear forms, localized pits left over from the stamukhas, standing on the bottom, have also been found. Thus, forms of ice gouging at depths up to 12 m were first instrumentally registered in the North Caspian. However, the issues of determining the maximum depth of the sea, where the exaration of the bottom by hummocky ice formations is possible, as well as the depth of their embedding in the ground, remain open for the Caspian [5].

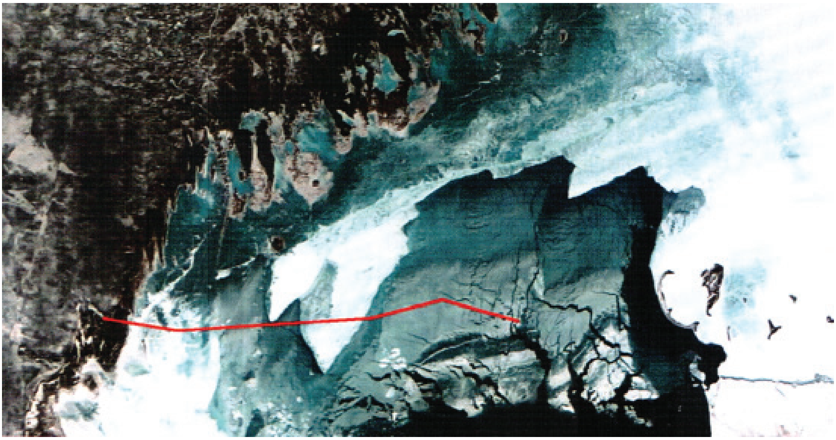

Figure 1. Planned pipeline route on the seabed of the North Caspian

AZOV SEA

The sea of Azov, despite the fact that its climatic conditions are generally less severe than in the North Caspian, is characterized by complex and variable ice conditions. This is due, primarily, to some morphological features that contribute to the formation of ice: the shallowness of the sea, low salinity of water and embayment. These factors are imposed upon frequent changes of the atmospheric processes in the cold season, leading to changes of ice area in the sea, as well as significant repeatability of winds of the east quarter, resulting in consolidation of drifting ice in the form of hummocks and layers along the western and south-western coasts of the sea. In January, the latitudinal factor is traced at the first stage of ice cover formation. In this period, the most difficult ice situation is usually observed in the northern part of the sea. Consolidation ratio of floating ice is 8–10 points. In the southern part of the sea, the ice is practically absent in the first decade of January, thin ice appears by the end of the month, the concentration of which generally does not exceed 7 points. In February, the ice situation at sea is the most difficult. The whole northern, western part of the sea and Taganrog Bay are covered with fast ice or extensive ice fields of white ice with concentration of 9–10 points. The least ice is in the exposed parts of the south-eastern part of the sea (density of 6–8 points, the probability of fast ice does not exceed 50 %). Such a distribution of ice in February is due to the fact that under the action of strong and prolonged east and north-east winds, the ice breaks up, cracks off the coast and superimposes on the opposite shore. The offshore winds squeeze the ice from the shore, causing its diverging, and the formation of polynyas. During strong negative surges when the sea level decreases, ice cracks appear in stationary ice. North-eastern and eastern winds are stable and persist sometimes for 10–13 days.

Complete freezing of the sea is observed in severe winters (but not every) and lasts usually less than two weeks. The fast ice decay starts in the second half of March and only floating ice forms are observed in the sea in early April. Final purification of the sea from ice occurs by the end of April, sometimes early May, about a month later than in moderate and mild winters. In shallow areas of the southern part of the Azov Sea, ice formations in the form of disorderly piles of ice debris are observed in winter. Their appearance, shape and size are subject to depth, bottom relief, intensity of ice drift, the presence of surging, and most importantly – the speed and direction of the wind. Most hummocking, as well as the maximum number of ice hummocks and barriers, is observed in the southwestern part of the sea, including the area of the supposed works. Significant angularity of the coastline, the repeated opening and freezing leads to an increase in hummocking of ice along the seacoast. In the area of planned works, the ice hummocking is about 1–2 points during mild winters, it reaches 3–5 points in severe winters, sometimes knolls (stamukhas) and hummocked ice appear. Usually the height of the hummocks is 1,0–1,5 m, sometimes it can reach 2 m (January 1957). In the harsh and sometimes mild winters, stamukhas are formed at a distance of 5–6 miles (10 km) from the shore. During mild winters, their height is 5–8 m in this area, and they can reach heights of 10–14 m in severe winters. Hummocky piles of 4–6 m, sometimes up to 8 m in height, prevail on coastal spits and shallows of the open sea (Figure 2).

In the twenty-first century, the duration of freezing of the Azov Sea and the North Caspian reached 50–70 days. Hummocks and stamukhas began to emerge. Ice situation has paralyzed the shipping industry for two months [6].

ARAL SEA

The world is well aware of the so-called Aral disaster. As a result of use of the flow of the two Central Asian rivers – Amu Darya and Syr Darya for irrigation, as well as other types of water consumption from these sources and the effects on them, in the end, these watercourses have ceased to reach the delta at the inflow to the Aral

Sea. As a result, the water area of the Aral Sea began to decrease quickly. The Aral Sea lies in the southern zone, but ice is formed there annually. The ice formation usually begins in the coastal areas in the north and north-east of the sea around the second decade of November. By the end of this month, primary forms of ice appear on the south coast. In the open sea, ice can be observed from the second decade of December, and near the west coast it is formed on average in the first decade of January. The ice cover reaches the greatest development in mid-February. The coastal zone of the sea is covered with fast ice and in open areas, there is drifting ice represented by small and large ice pieces and ice fields. Spring sludge of ice usually begins in the second half of February in the south and in the first half of March in the north. However, in cold spring on separate areas of north and east coasts, the fast ice may be preserved up to 20 to 25 of April. As a rule, the melting of ice is intense. By mid-March, the ice coverage is reduced by 25%, and at the end of April the sea is completely free of ice. On average, the ice in the Aral Sea has remained for 4–5 months, and sometimes for six months. Ice exists in the western deep part of the sea for the shortest time.

Figure 2. Heaps of ice in the coastal zone of the Azov sea

Marks (lines) of the Aral Sea on the drying seabed in 1990 were first discovered by B. A. Smerdov. "Revealed contours represent various figures with single or multiple parallel lines of unusual shapes. They are very similar to stripes, ruts and gouges of width from 2–5 to 20–50 meters and length of 100 kilometres, accompanied by piles of soil on the sides, recalling the tracks of a bulldozer. On the one side, these lines have smooth inputs, and, on the other side, at the output, they end with transverse "bundles" of tangled stems and rhizomes of aquatic plants interspersed with small shells. Similar contours, indeed, could be formed in the process of moving or drawing of any big items on sandy-muddy bottom of the Aral Sea, similar to the lines found on the bottom of the Caspian Sea in the north" [7]. When conducting in-depth geological and survey works in the southern Pribalkhash, in the area of known Karamergen ancient settlement, in the slopes of sand dunes at heights of 10–15 m, large blocks of stone ranging from 2 to 3 meters in size or more were found. These rocks compose rocky and stony shores of the northern part of Lake Balkhash and its islands. As noted above, in the XII–XIII centuries on the territory of modern Kazakhstan, global warming was undergoing, which in the middle of the XIII century led to the melting of glaciers in the mountains of Dzungarian Ala Tau, Tien-Shan and raising of the water level in the Balkhash-Alakol cavity up to 40 meters or more. The northern shore of Lake Balkhash with its rocky stony shores was flooded. Numerous islands with boulders, slabs and various shaped stone blocks were formed. As a result, at the time all existing lakes, such as Balkhash, Sasykkol and Alakol were a single water reservoir. Almost all of the Balkhash-Alakol lowland with settlements (including Karamergen), agricultural settlements and fields around them, located in the valleys of the Ili, Karatal, Aksu, Lepsy rivers, were under water. Since the XIV century, there is a period of severe winters, causing the surface of the Balkhash-Alakol water body repeatedly covered by ice up to 1 m in thickness, thus capturing and enveloping all the rocky outcrops of the shores and newly formed islands with boulders and rocks. With the onset of spring warmth, the water level in the water reservoir has risen and ice blocks with captured boulders and blocks of rock under the influence of north-eastern wind and currents started to move along the surface of the reservoir towards the southern Pribalkhash area. Then they hung up on the dunes and began to melt while further warming, leaving boulders and blocks of rock. A similar situation has arisen in the Aral and Caspian seas, and adjacent Torgay hollow, when in the process of completing of global warming in the middle of the XIII century, the water level rose to 10 meters and more, combining them at some time in a single water body. In those days there were numerous hills and ledges on the areas of the coastal zone of these seas, with rock formations and boulders of rocks, which have been turned into islands and peninsulas during the rise of the water in the seas. With the onset of the little ice age with severe and cold winters, the surface of the Aral Sea and the northern part of the Caspian Sea in winter was covered with ice of up to 1 m in thickness. However, those ice fields on the Aral Sea were short-lived due to strong winds and currents. The maximum speed of the winds during spring storms reached 30 m/s. The observers noted the most intense and prolonged manifestation of the winds on the western coast with the dominant north-eastern vector. Under the influence of winds and discharge currents of the Amu Darya and Syr Darya rivers, drifting ice fields interacted with the bottom, islands and peninsulas, which led to uneven drift of ice floes. The drift was accompanied by deformations, shifts and hummocking of ice fields, with the formation of cracks, leads and ridges. At the low depth of water reservoirs, the soles of ice hummock ridges reached the seabed and made gouges on the bottom while drifting of ice floes with ridges, especially during the spring storms. The most intense accumulation occurred in areas of islands and peninsulas that inhibited the movement of ice floes. They broke apart, forming hummock ice ridges, which then turned into motionless, settled on the bottom ice ridges – stamukhas. Such movements of the ice floes with ridges repeated many times over many decades, and maybe centuries, leaving in the end numerous field gouges on the bottom of the sea. Ice-exaration relief forms can be found on land. Such relief forms were found while analyzing satellite images and aerial photographs on the former bottom of the north-eastern coast of the Aral Sea (Figure 3).

These forms of relief were discovered and described by B.A. Smerdov "...with going in and out gouges and lying across bundles of rolled up seaweed and small shells at their ends" [7]. In his article "One theory of origin of Aral and Torgai geoglyphs in Kazakhstan", I.V. Stasiv gives a detailed description of these lines "marks" of the Aral Sea, and makes a conclusion about their natural origin [8].

Figure 3. Gouges of ice exaration in satellite image of the Aral sea coast, the scale of the image – 4×6 km (Scanex)

LAKE BALKHASH

Lake Balkhash had different names: Si-Khay "West sea" – in Chinese, the AK-Dengiz – "White sea" in Turkic and Mongolian, Tengiz "Sea" – in Kazakh.

The name of Balkhash lake was charted on the map of Y. Klaport in 1833. The place name means "marshland" or "swamp with tussocks". The lake is located in the arid region. North of the lake, there are the mountains of the Kazakh Upland, to the south – sands of Saryesik-Atyrau, Taukum and Chu-Ili mountains. The main rivers that nourish the Balkhash lake are Ili, Ayaguz, Lepsy, Karatal and Aksu. Natural uniqueness of the lake lies in the different indicators of the salinity of Balkhash in western and eastern parts of the water area. The narrow strait at the Saryesik peninsula divides lake Balkhash into two parts, the western part with the freshwater and the eastern part of the brackish water (Figure 4).

Figure 4. Lake Balkhash. Satellite image

In the winter months the lake is covered with ice. The origin of Balkhash is connected with the melting of ancient glaciers. During the last ice age, the total area of the united Balkhash and Alakol lakes reached 102 thousand km^2. In those days the lakes had a depth from 100 to 200 m. After the end of the ice age when the ice retreated high into the mountains, the lakes were divided and gradually began to dry and sink. At the same time the water began to get salty. Clear separation of the lake into two parts is quite natural, the width of the Uzun-Aral strait, that separates the shallow and freshwater west and deep saline east, is only three kilometers, which is very small compared to the total width of the lake. Four-fifths of the whole volume of water flows into Balkhash from the Ili river, which flows into the Western part. Several small rivers provide the inflow of fresh water, though insufficient, into the eastern part. Among them, the rivers of Aksu, Karatal, Lepsy and some others. The water level in Lake Balkhash is subject to long-term and short-term fluctuations. The minimum water level that is at

12 to 14 meters below the current one was observed in the period from the fifth to the tenth century, and the maximum from the thirteenth to the eighteenth century. Short-term fluctuations were registered in the observations in the years of 1958–1969, when the lake area was 18 thousand km^2. In dry years of 1990s and 1930s, the water level has dropped by three meters, and the area decreased to 16 thousand km^2. Lake Balkhash has a very winding coastline with many bays and coves. The lake has very few islands, the largest of them are Basaral and Tasaral. Cool summer with average temperature in July is about +24 °C, and cold winter – in January the average temperature is equal to minus 8 °C. There are around 120 millimetres of rain annually in the lake region.

Every winter the Balkhash lake is completely frozen over, the lake is under ice from November to March-April. The thickness of ice can reach 70 cm, the ice period is 120–140 days. In spring, under the influence of heat, wind and currents, the ice begins to break up and drift. Hummocks are formed, which begin to interact with the ground in shallow areas, and often encroach to the shore, forming a heap of hummocks, the height of which is up to 3 meters or more.

CONCLUSION

Studies of gouging of the seabed and the shores with ice formations of frozen shallow water bodies of southern Eurasia are in their embryo state. Ignoring this issue by oil and gas companies, the position of which was considerably reinforced by the conversations about global warming and the impending total disappearance of the ice cover on these water bodies, has led to the situation that most of the projects were implemented without regard to ice effects on the bottom and underwater structures. So, almost all underwater pipelines in the North Caspian Sea are not buried in the ground. As a result, there was an accident in the Kashagan oil field in the Kazakh sector of the North Caspian, where ice damaged four runs of pipeline laid on the bottom without embedding. To date, the question about the intensity of impacts on the seabed of the North Caspian remains open and requires further research. On the one hand, the complexity of problems is determined by the insufficient study of the processes of interaction of ice cover with the soil base of the seabed, on the other – the diversity of tasks due to extremely high variability of the level position and ice cover of shallow freezing waters of the south of Eurasia. For reliable determination of the required by science and practice characteristics, and detailed understanding of the problem considered in the report, a systematic and orderly study of the gouging processes of the bottom and shores of these water bodies is necessary. The present study is only a first step on the path to solve the problems. Climatic and anthropogenic changes of any sort can lead to a radical transformation of the natural environment and change of conditions of formation and preservation of ice-exaration relief on the bottom of the freezing seas.

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SALT DOMES INFLUENCE ON ICE FORMATION PROCESSES IN THE NORTH CASPIAN SEA [10]

ABSTRACT

During the longstanding ice air-reconnaissance, the observers notice the polynyas in those shallow areas of the North Caspian, where they expect the thick stationary ice (shore-fast ice). Attempts to explain its formation by dynamic factors only (under-ice currents, ice drifting) did not produce any good result. With artificial satellites emerge the data on the Caspian ice increased drastically. Analysis of ice cover state and dynamics data allowed to make a conclusion, that some polynyas form annually in the same locations of the North Caspian. Brusilovsky (1986) supposed, that the polynyas locations may be related to salt domes presence in the water areas of the North Caspian. The Caspian waters dissolve salt domes peaks, leading to local water salinity growth, which in a cold season results in delay in ice forming above the salt domes. Consequently, there form the polynyas. In summer months, local focuses of higher water salinity can hardly be disclosed due to winds, waves and currents. The research should be continued to receive a more detailed hydro-chemical description of the coastal area marine waters in the Caspian Sea (above the salt domes) during a winter season.

SATELLITE ICE DATA

Thanks to space technologies development during the 1970-s, radically new and promising methods for hydrological conditions study were developed, including ice processes in seas and oceans. This was facilitated by creation of the satellite information autonomous receivers network. In 1975, such receiver site was created in Astrakhan on the basis of the Astrakhan Zonal Hydro-meteorological Observatory (AZHMO). In winter 1976, for the first time ice cover television pictures were used for precise determination of ice edges and boundaries location acquired from ice air reconnaissance at the Caspian Sea. A simple optical-graphical method was employed for decrypting the satellite television pictures and mapping the ice situation. Informative value and accuracy of these ice maps received was successfully augmented by synchronous shooting. A comparative evaluation between the ice maps accuracy, which were acquired from the Meteor spacecraft, NOAA satellites, etc. and maps of synchronous ice air reconnaissance revealed a satisfactory coincidence of shore-fast ice boundaries, margins of drifting compacted ice, as well as dimensions and location of flaw polynyas, which were averagely 3 miles (5,5 km) across. While the satellite information receiving and processing took a minimum of time

[10] Salt domes influence on ice formation processes In the north Caspian sea / Buharitsin P.I. // Материалы of the 24th International Conference on Port and Ocean Engineering under Frctic Conditions POAC,2017. Busan, Korea, june 11–16, 2017. (электронный вариант, на флэш-карте). – P. 1-11.

(20 to 30 minutes), it sufficiently increased the ice maps operativeness and quality. This offered using the satellite information as a basis for ice reconnaissance pre-flight briefing, coordinating routes for the next air reconnaissance with flight crews, correcting and accurate determining the ice situation in those sea regions, where the air reconnaissance was not carried out due to various reasons, as well, as their fast supplying for scientific purposes and for sea industries of domestic economy [2–5, 9].

REMOTE STUDY OF FLAW POLYNYAS

Satellite data provided an opportunity for monitoring formation, development and extinction process in one of the most important and changeable hydro-meteorological condition elements during winter in the North Caspian – the flaw polynya. The ice air-reconnaissance did not provide such opportunity because of insufficient monitoring frequency and data incompleteness. It was thought, that locations, where polynyas appear as well, as their development processes are determined by wind's speed, direction and duration effect, coupled by under-ice currents' speed and direction. The satellite data helped to reveal that with sustained and offshore winds blowing in the northern Caspian, between the shore-fast ice and the drifting ice, there appear polynyas several hundred metres to 10 miles and more in width, sometimes up to 100 miles or even more (Figure 1). Formation of these giant polynyas is facilitated by wind-drift currents, which result from wind effect blowing on sea surface free from ice. Ice situation may change rapidly with wind change. Drifting ice will close the existing polynyas, while new ones will form at the windward side [7, 8].

A compiled map shows vast flaw polynyas in shore-fast ice edge, shot by the satellites during 1980–1990-s, provided determining the North Caspian areas with a sustained shore-fast ice, i. e. sea areas, where stationary ice remains during the whole ice season from its formation moment to fracturing in spring.

It was revealed that during the ice cover formation period, the shore-fast ice movement to the south is not gradual, as it had been thought before, but leaping. Boundaries between older and newer shore-fast ice are often marked by hummock ice, several kilometres in size, which is similar to those forming in drift divides of arctic seas. They may be seen well on satellite pictures and decrypted easily. Thanks to aircraft and satellite data, we managed to trace gradual daily changes in ice distribution on the entire area of the North Caspian, which was not possible with any previously existing traditional methods. As a result, appearance, location and dynamics of ice leads and flaw polynyas in relation to wind direction, speed and duration effect was revealed. A sequence of shore-fast ice fracturing process in spring time was traced as well [6].

Although, for many years during ice air reconnaissance carried out in depth of winter, oceanologists have been noticing vast polynyas in shallow areas of the North Caspian, where, according to their calculations, they could not have been, but there should be a thick stationary ice (shore-fast ice) instead. Attempts to explain its formation by dynamic factors only (under-ice currents, ice drifting) did not produce any good result [1]. There should be some unknown reason, due to which they form (Figure 2).

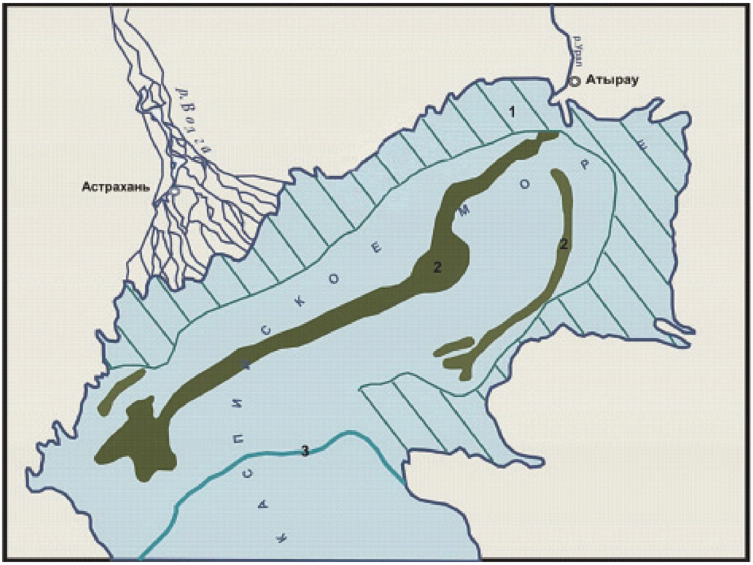

Figure 1. The North Caspian areas, where the polynyas form regularly, are marked in grey-brown

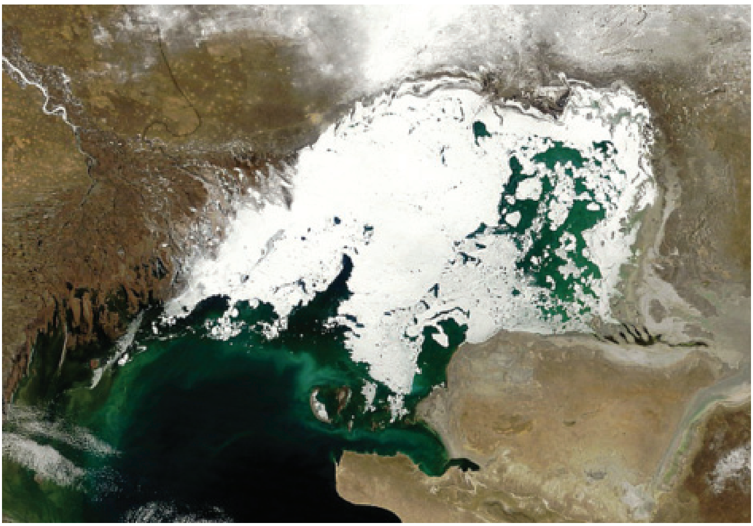

Figure 2. Polynyas in the northern Caspian ice cover (this photo was found on the Internet df67c592)

NORTHERN CASPIAN SALT DOMES

Brusilovsky (1986) was the first to suppose, that the polynyas locations may be related to salt domes presence in the water areas of the North Caspian (Figure 3).

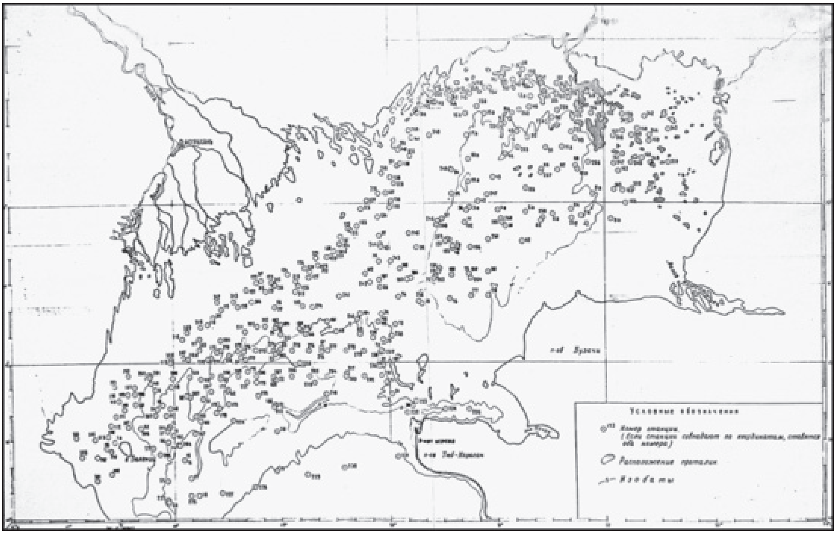

Figure 3. The diagram of salt tectonics and adjacent dry land in the North Caspian (Brusilovsky, 1978)

In 2002, a Russian book "Regional geology and oil-and-gas-bearing capacity of the Caspian Sea" by Glumov, et al., was published [11]. In this book, the authors draw a conclusion for many years of marine geological and geophysical research conducted by methods of seismic, electrical, magnetic, gravity and geothermal survey, drilling, geochemistry, seismology, etc., which was executed mainly by the VNII-MORGEO (All-Russia Scientific-Research Institute of Marine Geology and Geophysics) in the city of Gelendzhik. This is the former all-Soviet leading scientific institute (renamed many times), which set out hundreds of expeditions across the Caspian Sea, including those under supervision of B.N. Golubov. In their work scientist present a detailed diagram of salt tectonics and adjacent dry land in the North Caspian according to drilling, seismic survey and gravimetric data (Figure 4). Unfortunately, the authors did not make any mention in their book of the salt domes relation to ice processes in the northern Caspian, nor to the polynyas, in particular.

Marine hydrochemistry results, acquired by Gursky (2003, 2007), are also of an informational value. They are published in his Doctor of Sciences dissertation research, comprising 2 volumes. The diagrams acquired by him resemble much in details salt dome rise contours in the North Caspian.

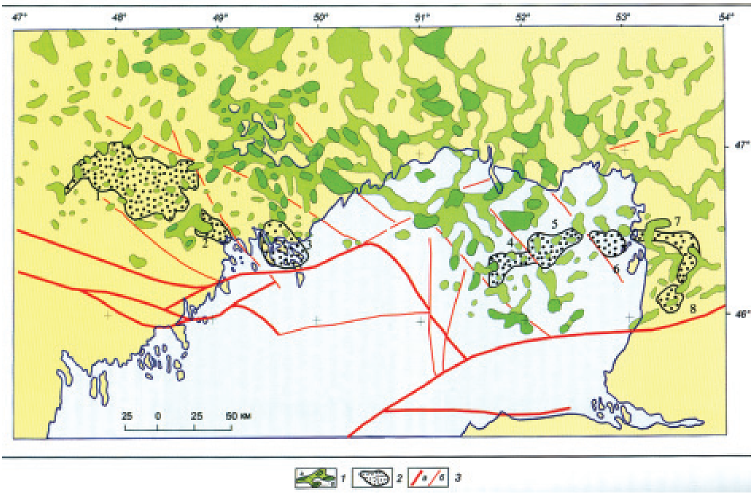

Figure 4. The diagram of salt tectonics and adjacent dry land in the North Caspian (according to drilling, seismic survey and gravimetric data) [11].
Map symbols: 1 – salt beds and masses (a) and local salt cores (b); 2 – subsalt bed protrusions; 3 – subsalt bed fractures: primary (a) and secondary (b).
Map figures: subsalt bed protrusions 1 – Astrakhansky, 2 – Imashevsky, 3 – Zhambaisky, 4 – Kerogly-Nubar (western Kashagan), 5 – Kashagan (eastern Kashagan), 6 – Kairan, 7 – Tazhigali-Karaton. 8 – Tengiz

The author analyses data acquired from many years of observations and proves the supposition made by Brusilovsky: stationary polynyas location practically coincides with salt domes outcropping in the northern Caspian Sea bed (Figure 5).

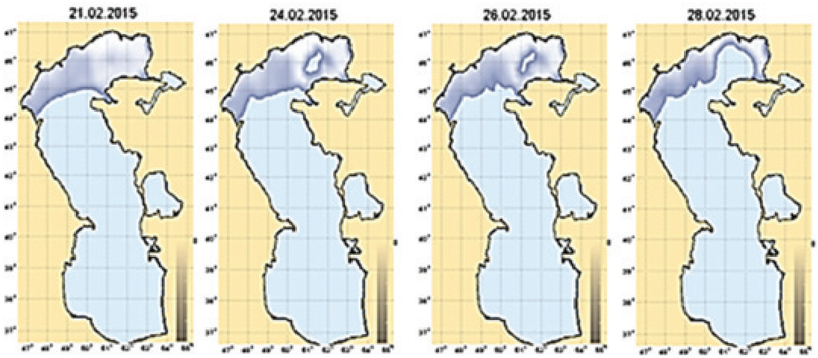

Figure 5. Diagram of the salt domes and polynyas in the North Caspian

The Caspian waters dissolve salt domes peaks, leading to local water salinity growth, which in a cold season results in delay in ice forming above the salt domes. Consequently, there form the polynyas. In summer time, waves and currents hinder findings of local focuses of higher water salinity.

FIELD RESEARCH ON THE CASPIAN ICE STRENGTH PROFILE

Many factors influencing ice strength lead to a large range of strength value, which is described in dedicated literature. Using the same devices and studying methods by the same researchers provided grounds to hope for better results accuracy and a much homogeneous data on the strength, which depends only on objective characteristics of the ice cover. The diagram resulting from many years of study is given in Figure 6 [10]. Systematic research on the ice strength profile in the eastern part of the North Caspian using a helicopter was conducted in winter season 1970–1971. Ice structure and strength study was conducted on open cut of Gurievskaya borozdina – Ukatny isle – Karakaisky bank site on 6th and 9th March, 1971. The ice thickness in the cut ranged from 27 to 42 cm. Tests of plates, obtained from cutting cylinder-shaped ice cores, revealed ice destructive stress value at compression related to its salinity (chlorinity). In all plate samples, its average value was 10–16 kg/cm.

On 29 January, 1972 a helicopter-assisted work was carried out to select the ice cores during the Caspian ice strength study in: Gogolskaya spit, its continental slope, Balashovsky, Suendykovsky, Kolkhozny sand islands, totally at 5 locations in the extreme east of the North Caspian. At the time of the study, the temperature was –19 °C, snow cover on ice 0–5 cm, sea depth in three locations was 60–70 cm, in two locations the ice lay on the ground 32–38 cm in thickness. The ice was slightly structured, homogeneous across its strata and matted, as a turbid water had been frozen. Lower strata had air bubbles. Snow temperature was –14,5°, under-ice temperature showed –0,4 °C…(–0,3 °C). It was found that the temperature in the ice cores increases from surface towards the sea depth. Thus, on the surface it showed – 13 ° …(–14 °C), while in the bottom part only – 5°, with the ice temperature growing faster from the surface. Difference between first 10 cm of the core was 3°, then 2°; 1,5°and, in the lowest strata 1,0–0,5°.

The ice chlorinity (salinity) in the considered samples increased along its depth. At the ice surface it was 700–900 mg/l and in lower strata – 1300–1500 mg/l. Destructive load for 100 ice plate samples, as tested by application-interpreted model was: 40–50 kg – for upper strata, 30 kg – for lower strata. The ice strength value varies from 7 to 3–4 kg/cm.

In January, 1973 the aircraft-assisted work for the ice strength study in the eastern part of the North Caspian was continued. Photography shooting was carried out on January 27 at nearly the same locations, as were in January, 1972. At the time of the study, air temperature was –7°, snow cover on ice 4–5 cm, the ice temperature –5,5°, upper ice stratum temperature –4,8°, ice temperature in near-water stratum was –1,5°, water temperature –0,2°. Thus, the temperature distribution in the ice strata measured in January, 1973 differed significantly from that of the previous year. Ice temperature increasing gradient did not exceed 1,0° (in 1972 it reached 3,0°) across all the ice strata.

The chlorinity (salinity) in different ice strata varied from 320 to 1,540 mg/l (Table 1).

Table 1

Comparison of ice chlorinity in eastern areas of the North Caspian in 1972 and 1973, mg/l

Average	Years		Average for 2 years
	1972	1973	
From surface ice samples	826	585	665
From bottom ice samples	1405	890	1062
From all samples	1085	685	835

Such difference in the ice chlorinity (salinity) value for the years given may be explained by ice formation peculiarities. So, during the winter seasons 1971–1972 ice formation ran quickly. Freezing water captured many salts, which, forming salt brine cells, filled in space between the fresh-water ice crystals, thus increasing the chlorinity (salinity) of the ice. While in winter 1972–1973 decrease in temperature occurred slowly. The ice formation passed gradually, with the salt brine leaking down into the water and increasing salinity of the under-ice water, at the same time, the ice chlorinity (salinity) was decreasing.

Like the chlorinity (salinity), average ice strength in 1973 proved to be sufficiently higher than in 1972 – 14,4 kg/cm. Near the same was an average strength in upper and lower strata.

For the two years (1972–1973), average value of the ice strength in all horizons was 10,7 kg/cm, and surface stratum average strength was 12,1 kg/cm [10].

The next stage of the ice study was measuring ice maximum strength in different areas of the North Caspian. This work was conducted from December 27, 1973 to February 3, 1974 at 30 equidistant points in the North Caspian water area. Air temperature at the core sampling points ranged from –1,5° to –18,1°, ice thickness was 11 to 43 cm, snow cover on the ice was 0 to 4 cm and water temperature under the ice was 0,85° to –0,26°. Water salinity at the surface (under the ice) varied greatly: from almost fresh at estuary seashores of the Volga and the Ural rivers to 20,52 ‰ in coastal area at the extreme east of the sea (Figure 6 and 7) [10].

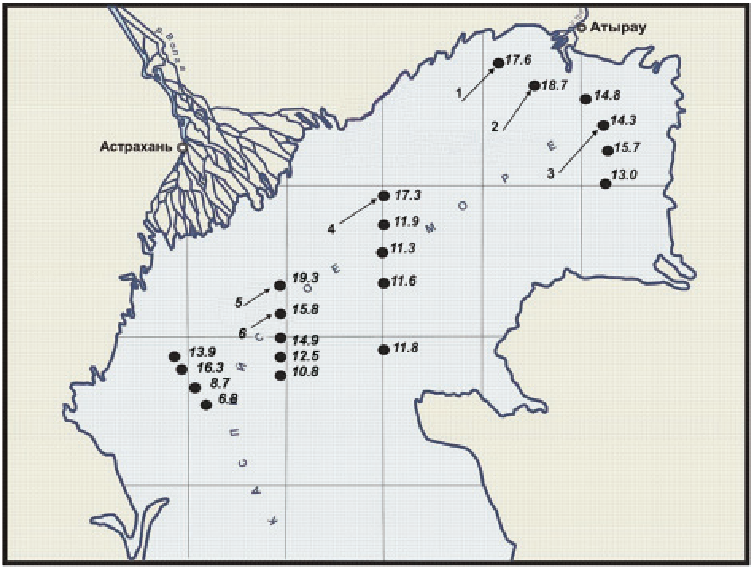

Figure. 6. The ice core sampling points in the east of the North Caspian.
Figures near the points stand for ice average strength in core, kg/cm^2.
Arrows show the points, data from which was used to draw the ice strength curves

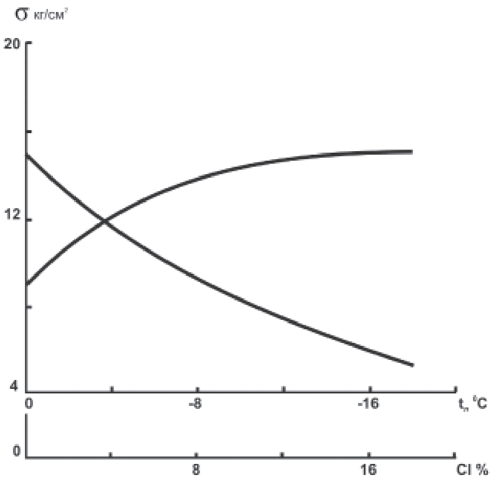

Figure 7. Smoothed ice strength values in the North Caspian related
to its temperature and chlorinity (salinity)

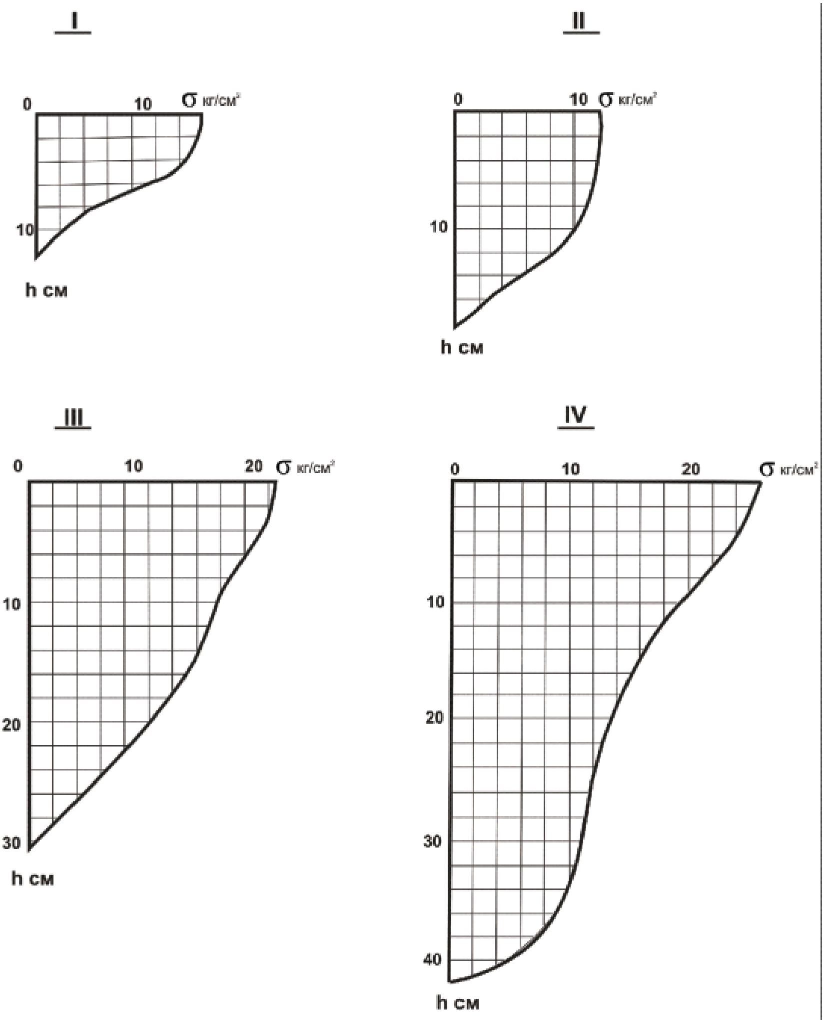

Figure 8. The curves of the ice strength at points located in the eastern part of the North Caspian:
1 – 27. XII.1973; **2** – 05.01.1974; **3** – 10.1.1974; **4** – 20.01.1974

CONCLUSIONS

Analysis of the gathered aircraft and satellite data proved Brusilovsky's supposition, that some polynyas in freezing shallow areas of the North Caspian Sea form annually in the same locations.

The most probable factor facilitating their local formation is the least strong and thick ice, which forms above the salt domes, and with wind and currents, it is destructed easier than a stronger ice formed from almost fresh water of the Volga and the Ural rivers falling into the northern part of the Caspian. The field research results obtained during wintertime studies 1970–1973 prove this supposition completely.

The research should be continued to receive a more detailed hydro-chemical description of the coastal area marine waters in the Caspian Sea (above the salt domes) during a winter season.

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THE BOTTOM ICE IN THE NORTHERN CASPIAN SEA [11]

ABSTRACT

The first regular study of sea ice in the Northern part of the Caspian started in the early 30s of the last century. Since then there was a lot of work done to define monthly ice edges, thickness distribution ice drift and ridging. Physical and chemical properties of ice such as strength, salinity and density were tested as well as properties of under-ice water with growing intensity since the first expeditions then. However, frazil ice as one of the most important ice types as one of the most important ice types in the area was not thoroughly studied. This work is one of the first ones that attempts to describe frazil ice formation process and estimate its effect on development of ice cover in the Northern Caspian.

INTRODUCTION

The study of the ice cover of the freezing seas of Russia is acquiring now growing importance both for scientific and practical purposes. Ice cover hinders navigation, hampers to a considerable extent development of natural resources and construction of offshore structures, seafood production, etc. At the same time, ice can serve as a quay, an airfield or even a temporary protection dam. Development of reliable reference manuals, as well as improvement of existing methods and creation of new methods for forecasting natural processes and phenomena are not possible without considering the influence of the ice cover.

One of the most important characteristics of ice cover is the thickness of thermally grown level ice. The processes of natural (thermal) growth of ice, were investigated in detail by N.N. Zubov back in the 1930-ies and many others afterwards. His assessment of the severity of winters in terms of "the sum of freezing degree-days" was included in hundreds of regional design formulas that made it possible to calculate the maximum possible thickness of level ice. His empirically derived formula is still widely used operationally [1].

While it is difficult to observe ice growth processes in-situ the formulae are verified with regular instrumental measurements showing discrete results. It is even more difficult to estimate contribution of frazil ice into overall ice thickness growth near opening leads or polynyas, while it forms in the layer of supercooled water as thermal growth and frazil ice formation take place simultaneously.

Ice charts, as a rule, report stage of development that is visually defined with means of remote sensing not the thickness. The stages of the ice are shown with symbols and correspond to a certain thickness range. Considering the uncertainties

[11] The Bottom Ice in the Northern Caspian Sea / Buharicin P.I., Buharicin A.P. // ISSN 2414-6331. Материалы 24th IAHR International Symposium on Ice Vladivostok, Russia, June 4–9, 2018 (электронный вариант, на флэш-карте). – P. 111-117.

with monitoring and defining ice types and their correspondence to ice thickness ranges there is only more questions arise in regards of early stages of ice development to accurately corelate them to thickness.

FRAZIL ICE PHENOMENA

Formation of the frazil ice in the Arctic seas was investigated by N.N. Zubov et al and many other researchers. However, the physics of the phenomenon itself, and, most importantly, the analytical form of its description, which makes it possible to quantify the fraction of frazil ice in its total thickness were proposed by E.I. Monakhov only in 1989.

His work has shown that the content of the frazil ice averages 5–10% in the Arctic and Antarctic seas, but it may reach 30–50% and even 70–100% over local areas such as opening leads, polynyas, pre-coastal zones estuaries with fresh water inflow, [2].

Multiple break-ups of pre-coastal fast ice causing drift events, hummocking and formation of huge open water leads, and polynyas occur through winter ice seasons under influence of strong wind events. Wind direction variation through the season results in repetitive opening and closing of leads forming in one place and closing in the other. Under the influence of wind waves and negative air temperatures over opening waters of the leads, the entire water thickness is mixing with turbidity through the whole layer and is supercooled. Presence of a large number of nuclei of crystallization (the silt, sand lifted from the seabed and microscopic air bubbles) in the water column initiates intensive formation of frazil ice, which partially floats up to the surface of leads accumulating in form of slush, and subsequently freezes forming opaque ice cover (Figure 1).

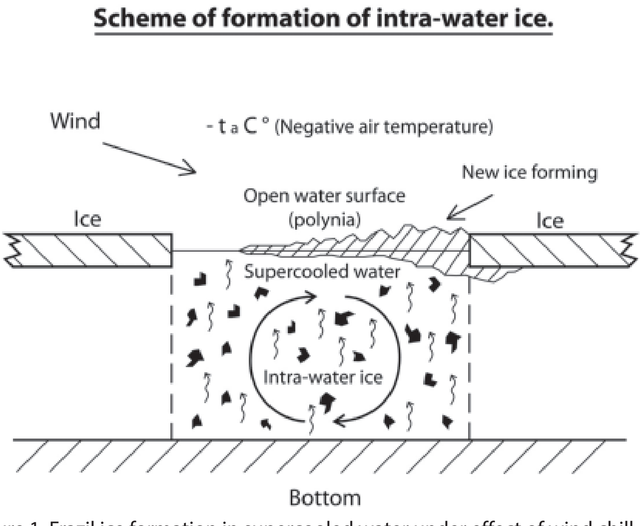

Figure 1. Frazil ice formation in supercooled water under effect of wind chill due to wind and negative air temperature

Due to the floating mass of frazil ice being very ductile during the freeze-up it often forms specific wavy surface under the influence of wind (Figure 2). Some of the frazil ice is also partly drifted away by current and emerges underneath surrounding older ice. As it floats up it freezes to the bottom surface of ice around increasing the rate of its growth. When repeated many times, layered, porous and opaque ice is formed. Its total thickness may significantly exceed ambient thickness of thermally grown ice in the area. These processes are quite chaotic as they occur locally limited to the size of a polynya, or lead, with continuously changing dimensions and lifetime.

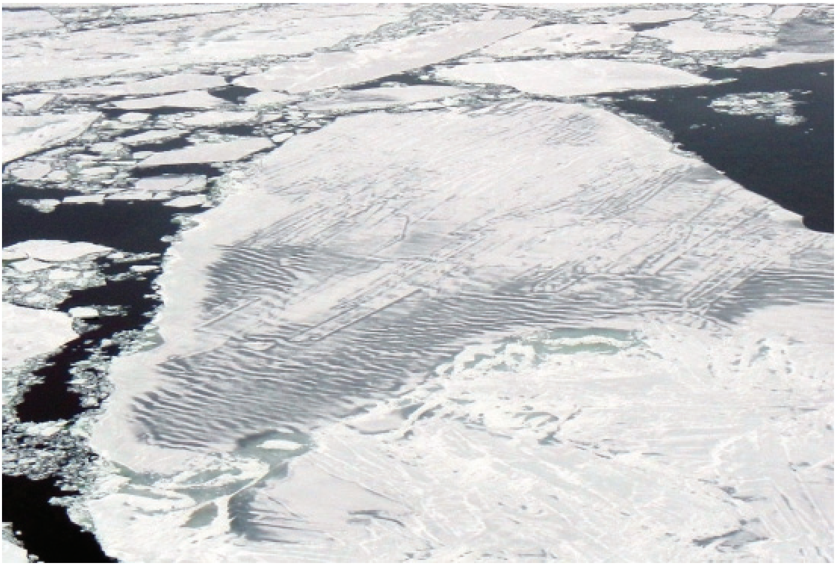

Figure 2. Refrozen frazil ice with specific wavy surface as observed on a floe during aerial reconnaissance flight

FRAZIL ICE PHENOMENA RECORDS IN THE CASPIAN

Analysis of more than 100 years archive records from the Caspian Sea has shown that, despite of almost no attention paid to the study of this phenomenon, the process of frazil ice formation was repeatedly observed by researchers particularly over ice covered shallow part of the Northern Caspian Sea. Works of F.I. Waller et al [1960–1990] showed that ice cover is forming and its thickness increases faster than can be predicted with Zubov's formula under the influence of negative air temperatures during the formation and development of ice cover in the shallow northern part of the Caspian Sea, because of rapid heat transfer.

The following are some of the cases indicating it:

In March 1953, while performing ice observations over reference profile in the mouth of Volga following significant drop of air temperature accompanied with strong wind and snowfall, intensive formation of frazil ice was observed over polynyas and cracks. It was in the form of opaque loose pieces of gray ice containing shells and pieces of algae (from the report).

In January 2002, during IB Captain Bukaev transit through Volga-Caspian Channel, the observers monitored the process of formation of frazil ice in over cooled water at slightly negative air temperature. It had form of ice crystals emerging on the surface and forming loose layer of primary ice forms with thickness ranging 2–5 cm and consisting of slightly frozen together crystals (from the report).

In 2016 formation of frazil ice was recorded with underwater camera in the central part of Ural Farrow during field work conducted there (Figure 3).

Figure 3. Snapshot of frazil ice lifting to the surface of newly forming ice

It should be noted that similar phenomena occur regularly in the lower part of Volga, after commissioning the Volga hydroelectric power station in 1959 Polynya downstream from the dam remaining open even during strong frosts acts as a generator of frazil ice, which is drifted downstream under existing ice in form of loose pieces with current. Sometimes cross-section of the river, is completely clogged with slush, which leads to formation of jams.

IN-SITU MEASUREMENTS

Thus, for example, for the identical sums of degrees of frost, the ice masses in one region of the sea may differ in thickness by a factor of almost two. The results of numerous instrumental measurements of the thickness of landfast and floating ice in the Northern Caspian showed that the minimum thickness of level ice was 45 cm while the maximum thickness reached 90 cm, which also indirectly confirmed contribution of frazil ice (Figure 4).

OPEN WATER LEADS

Thanks to satellite data becoming available during the later years possibility to monitor formation, development and extinction of the pre-coastal leads and polynya being one of the most important and changeable hydro-meteorological conditions during winter in the North Caspian. Air-borne ice reconnaissance missions of the earlier years did not provide such opportunity because of insufficient monitoring frequency and data incompleteness.

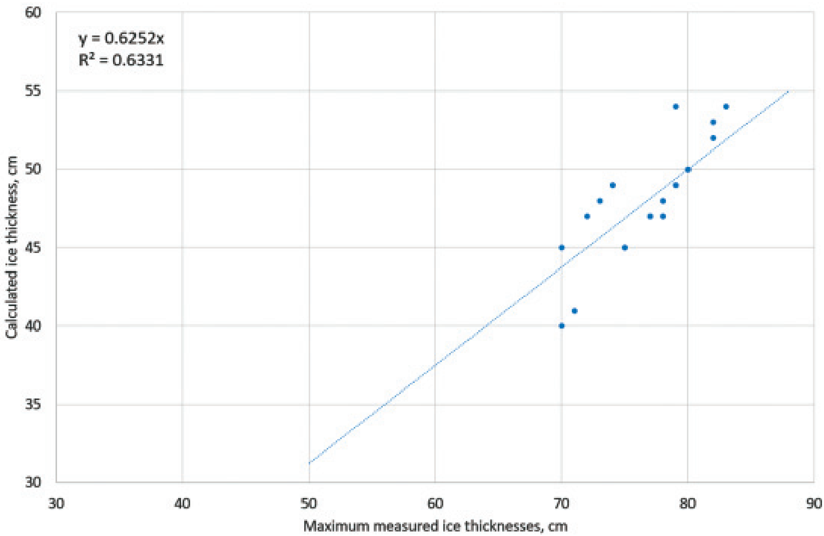

Figure 4. Measured maximum ice thickness compared with calculated with FDD

Locations, where polynyas and leads form and their development are determined with wind speed, direction and duration as well as under-ice water currents speed and direction. Satellite data helped to reveal that persisting seawards blowing winds result in leads opening between the landfast ice and drifting ice. They reach several hundred metres to tens of miles and more in width. Formation of these giant leads is facilitated with wind-drift currents, which result from wind drag over open water. Ice conditions may change rapidly with change of wind direction. Existing leads would collapse, while new ones will form at the windward side [3].

CONCLUSIONS

Analysis of ice charts compiled by UNOSIS and AARI in winter seasons 2013–2017 using satellite data showed high reliability and accuracy of such ice cover properties as the position of landfast and floating ice edges, polynyas and pre-coastal leads, compacted and open-pack ice zones, drift ice ccompactnes and ice floe sizes, and snow-cover on ice. However, one of the most important features, i.e. thermally accumulated ice thickness indicated on ice maps with respective symbols, does not correspond to the actual measured in-situ ice thickness.

Further study of frazil ice formation in the northern part of the Caspian Sea and its role in ice cover development will be undoubtedly be continued.

ACKNOWLEDGMENTS

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PARAMETRIC APPROACH TO GEO-ECOLOGICAL STUDIES OF HYDROCARBON DEVELOPMENT IN THE OFFSHORE AREA OF THE CASPIAN SEA[12]

ABSTRACT

The authors of the article consider the Caspian Sea as a geophysical mass in the form of a relatively thin layer of water above the structural levels of the Pliocene-Quaternary deposits, which is influenced by the following environmental opposite factors: on the one hand, geological and, on the other, climatic and hydrological. The parametric approach to the study of the driving forces of the environmental development of the Caspian Sea is based on the analysis of natural disasters over the past 70 years in the areas of offshore hydrocarbon production: powerful release of the earth's crust fluids (groundwater, mud, oil and gas) and catastrophic ice processes in the northern part of the Caspian Sea. This work contributes to the improvement of the theoretical foundations of geo-ecological and ecological-economic studies of offshore oil and gas developments, as well as contributes to raising public awareness in the problems of preventing accidents on oil platforms and the prevention of pollution of marine environment.

KEYWORDS: the Caspian Sea, natural disasters, fluids, ice ridges, oil fields, oil production platforms.

The Caspian Sea is the largest land locked body of water on Earth, located in the inner region of Eurasia, which was isolated in the Middle Pliocene about 5–6 million years ago. The body of water rests on a multi-kilometer thickness of water-, oil- and gas-saturated rocks of three groups of sedimentary oil and gass-bearing basins: North, Middle and South Caspian. The Caspian Sea is characterized by the presence of large reserves of non-renewable fuel and energy resources, a unique ichthyofauna, and also a coastal environment favorable for the development of resorts and tourism. In its depths, including in the Russian zone of the Caspian shelf, various types of ore and nonmetallic minerals are concentrated [16]. Among the latter, oil and gas deposits are of particular value (Figure 1).

However, the use of these resources can be seriously complicated by a number of dangerous natural phenomena and processes [2–6; 19; 21; 22]. The latter in this study are considered as parametric factors that can significantly change the ecological balance of the entire Caspian water reservoir.

[12] Ice-Gouging Topography of the Exposed Aral Sea Bed // Stepan Maznev, Stanislav Ogorodov, Alisa Baranskaya, Aleksey Vergun, Vasiliy Arkhipov, Peter Bukharitsin // Remote Sens. 2019, 11, 113; doi:10.3390/rs11020113. – C. 1-25.

Figure 1. The most promising sites of mineral recourses management in the Russian zone of the Caspian shelf. (Map compiled by the authors according to [14; 16])

RESEARCH CONCEPT

The Caspian Sea as an integral geophysical system: a traditional and new approaches to research. The traditional approach comes down to the notion that has been deeply rooted since the 18th century that this sea as a closed drainless water body with an impenetrable bottom, the water balance of which is mainly regulated only by climate, i.e. ratio of river runoff and evaporation losses. Therefore, the mechanisms of adaptation of the inhabitants of the Caspian Sea to abiotic environmental factors are seen in the action of only exogenous processes caused by the radiant energy of the Sun, the circulation of sea water and air masses, the work of surface waters flowing into it, the vital activity of organisms, etc. Accordingly, a scientific assessment of the impact of centuries-long economic activity on the state of the Caspian Sea mainly comes down to the analysis of chemical property and surface water regime. This creates a misconception that the supposedly "zero discharge" of anthropogenic pollutants is able to ensure the purity of the waters of the Caspian and thereby save the inhabitants of this sea, including seals, from extinction. The disadvantage of this point of view is that the lithosphere here is almost completely excluded from the abiotic and social links of the Caspian ecosystem.

A new parametric approach fills this gap focusing on the dialectics of the manifestation of geological and climatic-hydrological processes [18]. In this case we are talking about processes of a completely different geophysical nature, which have a common function expressed in their ability to cause serious damage to oil and gas fields and other types of economic activity carried out at the sea [13]. Our approach is based on the analysis of the data concerning, on the one hand, release of fluids of the earth's crust, i.e. groundwater (including metal-bearing solutions), mud, oil and gas, and on the other hand, catastrophic ice processes in the northern area of the sea We use as one of the illustrative examples, a very sad and little-known because of its secrecy, experience of the "ice battle" in the Caspian in the winter of 1953.

Standards for study and prevention of natural accidents in the Caspian Sea Though the number of natural accidents at offshore oil and gas fields is growing every year, a methodology for their forecasting has not yet been developed. Even after a detailed study of the structural geology and lithology of deposits using modern methods of marine geophysics and exploration drilling, opening of oil and gas deposits is carried out to a large extent blindly, without accurate knowledge of the geomechanics of the rock mass and the regime of reservoir fluids. In addition, it is now becoming increasingly apparent that the danger of reservoir fluid blow increases in proportion to the aging of oil fields and is most characteristic of abandoned ones. But, unfortunately, effective methods of escaping such a danger and "reclamation" of outdated fields are unknown. This generally abnormal situation is enshrined in the "Safety Rules in Oil and Gas Industry" (SR 08-624-03), which impose very strict requirements of the Russian Gosgortekhnadzor to the well construction (Section 2.2), as well as to the prevention of open flowing of wells (Section 2.7.7). But they do not indicate specific ways of implementing such strict requirements. The gap is observed in the state environmental acts: they also do not stipulate an algorithm for practical actions in abandoned marine fields. Therefore, following such runaround and vague "rules", field personnel are forced to act at their own risk, hoping for success in the scientific search for reliable ways to predict dangerous processes in the depths of seas.

Current trends of supporting the environmental safety of marine activities are usually based on the notion that the main sources of oil pollution of the seas are external, which include operations at oil terminals, tanker accidents, operational discharges from oil-containing waste ships, accidental oil spills on drilling platforms, etc. [11]. Therefore, the marine environment control system adopted in our country and abroad still proceeds from the fact that the so-called zero discharge technology is supposedly able to fully ensure the safety of offshore oil and gas production. Thus, in particular, the Law of the Russian Federation "On Minerals" (Article 24) requires users of mineral recourses to strictly comply with the "Oil and oil product spill prevention and response plan" (OSPRP), as well as the requirements for Maximum Permissible Concentrations (MPC) of polluting substances in the marine environment (Decree of the Government of the Russian Federation №613 dated 08/21/2000, as amended on April 15, 2002, №240).

In fact, neither the technology of zero discharge, nor the POPSR and the MPC requirements fully ensure the safety of a number of offshore oil and gas fields, since they unreasonably exclude any other types of danger. These are sudden releases from the depths of the seas toxic fluids (groundwater, oil and gases) or the so-called griffins, which are usually accompanied by geodynamic movements of the depths: earthquakes, subsidence or swelling of the seabed, underwater landslides, etc. Fountain hydrocarbon emissions (most often gaseous) account for 44,7% of the accidents and disasters in offshore fields. Most of these emissions (57%) result in ignition. In this case people die, drilling rigs and offshore oil fields are destroyed [9; 12]. According to Rostekhnadzor, in recent years on lands in Russia the average number of uncontrolled emissions has been 5,5, and explosions and fires – 5,1 [1].

In the context of the current expansion of the oil and gas industry on the Caspian shelf, there is a great need for reliable forecasts of accidents [11]. In this connection the Institute of Oceanology RAS (Russian Academy of Sciences), in common with the Institute for Dynamics of Geospheres RAS, Engineering and Technology Center "ScanEx", Roscosmos, Rosprirodnadzor, Institute of Oil and Gas Problems RAS, Institute of Geography RAS, Institute of Water Problems RAS, Moscow State University, Research Center for Space Hydrometeorology "Planet" and other organizations have joined in conducting multilevel environmental and geodynamic monitoring of shelf areas involved in the development of oil and gas resources of the Caspian Sea. The arsenal of modern monitoring methods and technical equipment used by the Institute of Oceanology RAS includes ship, underwater, satellite, seismological and stationary observations using bottom and buoy stations.

A number of documents serve as the basis for such studies: the Framework Convention for Protection of the Marine Environment of the Caspian Sea (Tehran Convention) for the conservation of the marine and coastal environment of the Caspian Sea and prevention of its pollution, the Marine Doctrine of the Russian Federation for the period up to 2020, approved by the President of the Russian Federation on July 27, 2001 (Order No1387), as well as the Protocol of the meeting of the Maritime Board under the Government of the Russian Federation of October 28, 2005 "On the creation of an comprehensive security system for oil and gas complexes on the continental shelf". This protocol prescribed, in particular, use of offshore drilling platforms as technological carriers for a comprehensive multilevel environmental and meteorological monitoring system, and in seismically active zones for geodynamic monitoring [1].

The main elements of a multi-level system, i.e. satellite, above-water, underwater, borehole and ground-based geodynamic monitoring have already been introduced and are performed in offshore oil and gas fields in the Caspian Sea, which are operated by the oil company LUKOI (Open joint stock company). Following the recommendations of the State Ecological Expertise of Rosprirodnadzor, the company's management, in collaboration with the Institute of Oceanology RAS in 2012, for the first time in our country approved the "Regulation of geodynamic monitoring" at the field named after Yu. Korchagin. Currently Lukoil is implementing such regulations in other Caspian offshore fields. Work is much weaker in organizing climate-glaciological studies of the occurrence, process and consequences of natural disasters similar to the 1953 "ice battle" in the North and Middle Caspian. Meanwhile an assessment of the intensity of ice and other hydrometeorological impacts that belong to the category of hazardous natural processes can be referred to a key link in the entire system for ensuring the industrial and environmental safety of oil and gas facilities in the Caspian Sea.

The complexity of the problem to be solved is determined, firstly, by the poorly studied wind-wave and ice impact on the Caspian oil and gas fields and, secondly, by the multifaceted nature of the tasks being solved due to the extremely high variability of the sea level position and ice cover of the Caspian Sea [3; 7]. It is known that fluctuations in the level of the Caspian Sea reaching several meters during the estimated period of operation of hydraulic structures can lead to a significant redistribution of depths. Accordingly, the conditions for the formation of ice ridges and their impact on the objects of the marine economy are changing [5; 6; 13]. A separate problem is in the secrecy of the materials required for professional analysis, diagnosis and prediction of catastrophic ice events in the Caspian Sea [15; 17].

Sudden emissions of mud, oil and gas from the depths Data on such natural disasters has been known since ancient times. An indicative example is the catastrophic collapse of the "60 Years of Azerbaijan" Self-propelled floating drilling rig (SPFDR) that occurred on September 9, 1983 near the eastern coast of the Middle Caspian. The drilling point was located in 23 km from the Cape Rakushechny, where the sea depth is 43 m. The calculated drilling depth was 4500 m. At a depth of 445 m, during the drilling of Oligocene clays, the washing fluid was interrupted by a breakthrough of gas-saturated formation fluids, and a sharp rise of mud solution from the interstring space began.

A gas fountain rose from a well to a 50-meter height and an intensive washout of soil began under one of the supports of drilling rig system. As a result the derrick shifted and crashed down (Figure 2). The accident at SPFDR "60 years of Azerbaijan" occurred at night in stormy weather. Two people died. The vessels arrived in time all night catching people from the water. Then the rescuers set fire to the gas so that it would not poison the atmosphere. A few days later the torch went out.

Figrure 2. A recent snapshot of the accident site of the "60 Years of "Azerbaijan" SPFDR

Another example is the accident at the "Tengiz" field in Western Kazakhstan (northeast coast of the Caspian Sea), which occurred on June 24, 1985. On this day, a powerful burning fountain of oil and natural gas saturated with hydrogen sulfide burst from a well of about 5 km from well №37 under a pressure of almost a thousand atmospheres. The fountain rose up to a height of more than 200 m, throwing a multi-ton string of drill pipes from the well to the surface and turning them into "pasta". At the same time, the nearby buildings were destroyed, and the fire raged for several months (Figure 3).

A team of liquidators was thrown into the fight against the accident, equipped with heavy-duty air transport for the delivery of equipment worth $ 2 million from the European warehouse "Cameron". The accident was eliminated only after four hundred days. As a result, plans to increase oil production in Kazakhstan from 18,7 million tons in 1981 to 25 million tons in 1985 were disrupted. This exacerbated the problem of a drop in oil production in the USSR that emerged in the 70s. According to some researchers, in the foreseeable future such an outburst of high-pressure reservoir fluids from the subsalt structural level of the southern edge of the Peri-Caspian Lawland may also occur in the Northern Caspian at the Kashagan field [4].

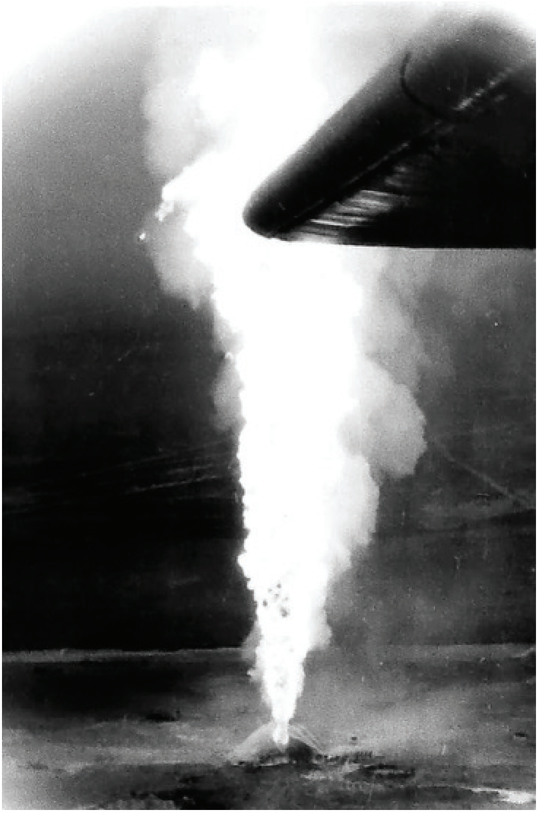

Figure 3. Burning oil fountain at the "Tengiz" field.
(The Aerial photograph was taken by P.I. Bukharitsin from a height of 150 m)

Not so long ago a new similar accident occurred in March, 2019 at the well of the Kalamkas field, located in the Mangistau region of the Republic of Kazakhstan, four kilometers from the Caspian Sea. Around the drilling site, 13 griffins formed – sudden breakthroughs to the surface of fluids (most often gas), moving under great pressure through the annulus of the boreholes. The accident was accompanied by a fire, which was completely eliminated only on April 4, 2019. The task of thoroughly studying the experience of dealing with major accidents on cross-border oil platforms is of particular importance. Thanks to television and the Internet, great many people became aware of the accident that occurred on April 20, 2010 at the Deepwater Horizon oil platform in the Gulf of Mexico (Macondo field) [10]. The platform got inflamed at 80 kilometers off the coast of Louisiana (USA), killing 11 out of 126 oil workers on it (Figure 4).

Figure 4. Extinguishing of fire on the oil platform in the Gulf of Mexico, April 21, 2010 (Photos from Yandex-pictures)

On the second day after the explosion, this platform sank, having appeared on the seabed at a depth of about 1,500 m. Over the next six months, about 5 million barrels of oil spilled into the waters of the bay from its depths. To eliminate the consequences of the tragedy, British Petroleum Corporation spent a colossal sum of $ 42 billion. It should be noted that the subsequent oil spill became the largest in the US history and turned the accident into one of the largest technological disasters with a negative impact on the environment (Figure 5).

The blockage of a deep well in the Gulf of Mexico required a tremendous strain of intelligence, technical and organizational capabilities with attraction of achievements of underwater robotics. All in all, 5 thousand vessels and 40 thousand people participated in the operation. They started drilling of two discharge wells. Moreover, shutting-in of the well did not solve the problem of pollution control of the bay and the coastal zone. This problem stretches over many years and involves huge financial costs. The accident in the Gulf of Mexico is a serious warning to all oil companies which, in the pursuit of profit, are ready to take significant risks by mining offshore [10]. Obviously, repeat of such an accident in the Caspian Sea can turn this sea into a complete zone of environmental disaster.

CATASTROPHIC DRIFT OF RIDGED ICES

The ice battle of 1953. Estimation of degree of impacts of ice formations in the northern part of the Caspian is an important aspect in ensuring the safety of hydrotechnical structures built in the water area of this sea [20; 23]. The development of oil and gas resources of the Caspian Sea dictates the need for thorough study of ice impacts on hydrotechnical systems [5; 17]. However, inferential research of the catastrophic drift of ice ridges is important, taking into account the laws of hydrodynamics of the Northern and Middle parts of the Caspian Sea (Figure 6).

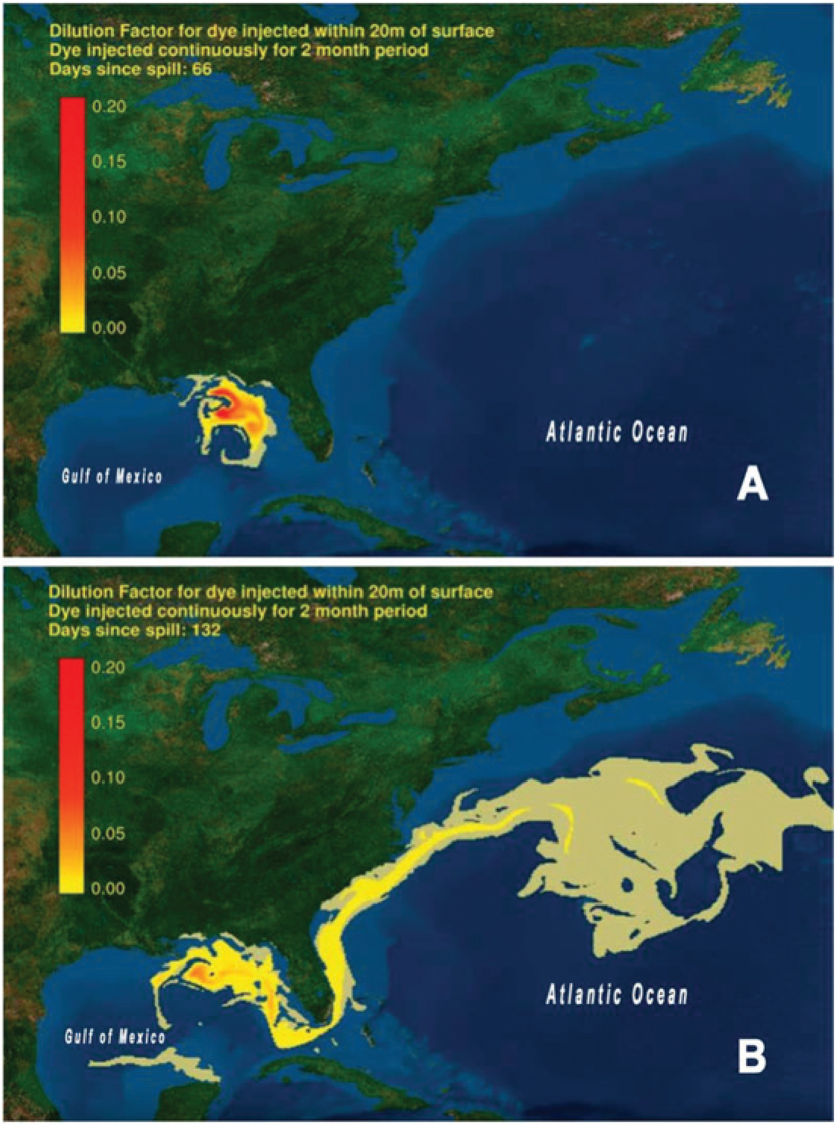

Figure 5. Gulf of Mexico oil spill propagation model, 66th (A) and 132nd (B) days after the disaster of April 20, 2010 (Source: [24])

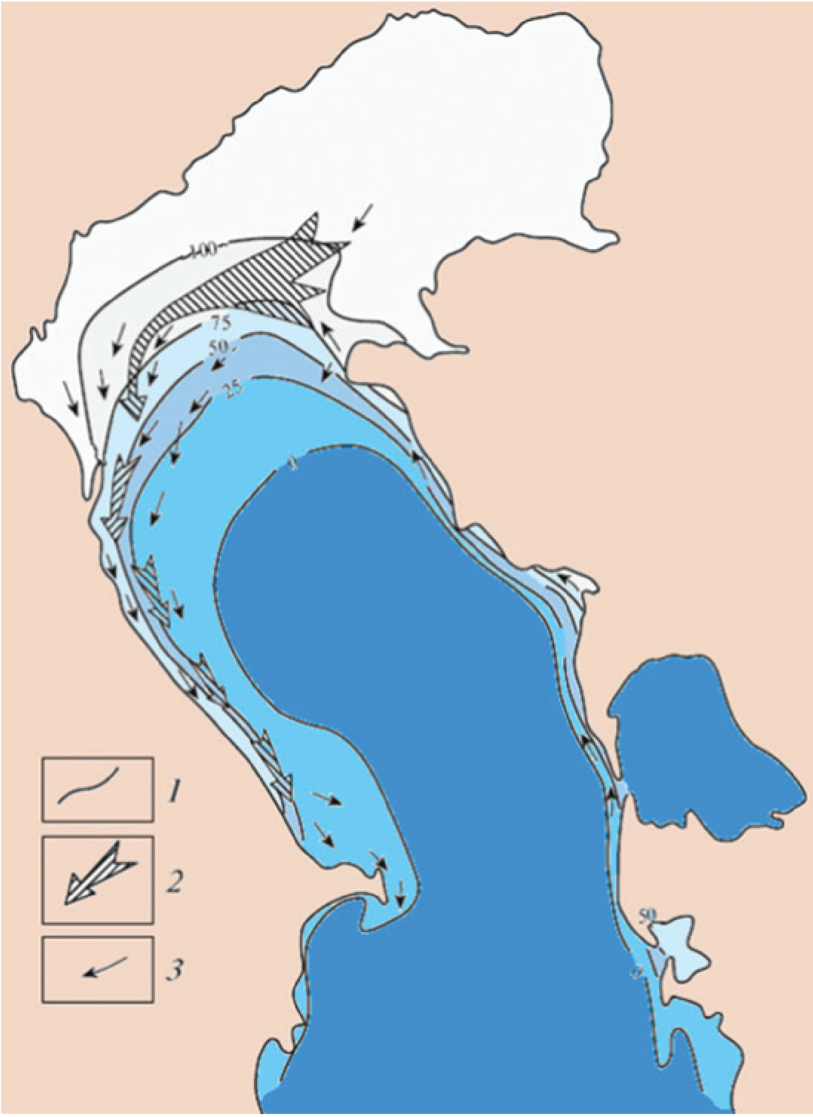

Figure 6. The probability of ice formation and directions of ice drift (Source: [8]):
1 – the contour of the probability of ice formation, %; 2 – general direction of drift;
3 – prevailing direction of drift

The lack of reliable estimates of the intensity of the impact of ice ridges on the environment can lead to damage to engineering structures, including subsea pipelines and oil platforms. Thus, great cognitive value has the description of events that occurred in the western coast of the Caspian Sea in the winter of 1953 and were first published in the open press in the article by Artyom Simonyan ("Science and Life", № 6, 2002), who in those years worked as the chief engineer of the project of marine hydraulic structures at the "Gipromorneft" Institute [15]. He tells that in consequence of sharp warming in the northern part of the Caspian Sea, huge ice fields broke away from the fast ice and, driven by wind and sea current, sailed south. The first obstacle to the ice floe was the Izberbash field (Figure 7).

Figure 7. Ice ridges on the approaches to the piers of the Izberg-Sea oil field in February 1953 (Photo from the archive of "Rosneft-Dagnefte" OJSC)

Understanding the complexity of the situation, the government of the Dagestan Autonomous Soviet Socialist Republic decided to bombard the ice on the far approaches to the oil field and sprinkle the ice shell with coal powder for more intense melting. But neither one nor the other helped. The ice shell tightly squeezed the structures of the Izberg-Sea, and its destruction began. "The piers and platforms one after another fell apart like houses of cards. There were no icebreakers in the Caspian at that time, and even if they were, they could not cope with the force of nature. Two days later, only distorted fragments of structures stuck over the ice floes", – writes A. Simonyan [15]. To a lesser extent the piers of the Inchkhe-Sea deposit, located a few kilometers from the coast, were destroyed.

The ridged ice quickly moved south, and two days later a real ice battle began on the oil-producing piers of the Apsheron peninsula. When the ridged ice began to demolish the supports of piers, the military began to use explosives. The ice crumbled at the supports, passing part of the ice under them, but it immediately began to crush with renewed vigor and the spans went under water. Thus, huge sections of piers of 300–400 meters long with pipelines laid along them, power cables with lighting poles and platforms with operating wells slowly went to the bottom of the sea. Fortunately the oil workers managed to kill the wells and prevented the oil spill. Ice floes destroyed the oil fields of Artem-Sea, Gyurgyany-Sea and moved towards the Oil Rocks. This was the worst test for the oil industry, perhaps, in the entire history of their offshore production in the Caspian. Weather reports daily convinced that the tragedy is inevitable for the Oil rocks. The management of the oil field decided to shut off the existing wells and send all personnel to the shore: drillers, operators, electricians, builders, and doctors. There were only 50 officers on duty. This was a team consisting of firefighters and workers, two meteorologists, two radio operators and two specialists from "Azmorneft". They were faced with the task: to prevent a fire and if and when the structures collapsed, retreat to the south side of the oil field, where three torpedo boats of the Caspian flotilla were waiting for them in clear water.

When the ice floes came into contact the first object of the Oil Rocks, a completely unexpected thing happened: the wind, blowing for many days from the east, instantly died down, and then, rapidly gaining strength, it blew out from the west. The ice stopped for a short while and sailed to where it came from. It warmed sharply, and they began to melt quickly. The people did not expect such an event. They were convinced that the tragedy on the Oil Rocks is inevitable [15].

After the "ice battle", drillers and builders had a rush season. They began to restore lost wells, piers, sites and other hydraulic structures. Simultaneously they began to repair wells. And half a year later all the oil fields of Apsheron went into action newly. Oil production reached its previous level and quickly even exceeded it. As for the Izberg-Sea field they decided not to restore it because of the poverty of the oil-bearing layer.

Unfortunately, climate-glaciological studies of the occurrence, process, and consequences of hazardous natural processes in the Caspian, similar to the "ice battle" of 1953, have not yet been practically carried out. The effect of drifting ice on shipping. All information on the ice thickness of the Caspian Sea, obtained as a result of long-term observations, is data on natural (thermal) build-up ice. The maximum thickness of such ice in the Northern Caspian is observed in January-February. But even in very severe winters its natural thickness, as a rule, does not exceed 50–60 cm in the northwestern and 80–90 cm in the northeastern part of the sea.

As experience shows, in the Caspian Sea ice cover is most often found in the form of pods and layers, the thickness of which significantly exceeds the thickness of the ice of natural growth. Strong winds, especially in the initial period of its formation contribute to the break-in of fast ice, drift and intense movements of floating ice. With thickness of 1 to 30 cm multifold laying of the ice takes place.

The areas of the most intensive shifts in the North Caspian include the Astrakhan Sea Raid and the marine part of the Volga-Caspian Canal. In mild and moderate winters, the thickness of layered ice mainly depends on the wind, and in severe winters the influence of wind is weakened due to strong fast ice. Due to the shallow water and significant fluctuations in the level of the Caspian Sea because of non-periodic water Raising-Lowering processes using wind, the ridged ice interacts with the bottom, forming gouging channels [5; 6].

The width of such gouges varies from a few meters to 50–100 m or more. All gouges end in shafts formed by plowed soil. The height of some gouges exceeds the depth of the sea and they reach the surface in the form of islands (Figure 8).

Figure 8. The ephemeral islet formed as a result of the plowing action of ice.
(Photo by F.I. Waller)

Plowing gouges, light against the background of a darker bottom are clearly distinguishable from an airplane. A large number of gouges are observed in the North Caspian in spring, after cleansing from ice, when the water has not yet been stirred up by spring storms. Their density reaches 20–50, and in some places of 100 or more gouges per 1 km of the route. The duration of the existence of gouges in muddy soils is 2–3 years; in sandy soil, furrows are washed away by wave agitation for one season. Ice drift often leads to dramatic situations in the marine part of the Volga-Caspian Channel. During a sharp increase in the east and north-east winds,

large masses of ice break away from the ice field in the central part of the North Caspian and begin to move to the west coast. At the same time, serious threats arise for ships moving along the marine part of the Volga-Caspian Channel. So, in February 1981, a large bulk carrier "Baku" with a displacement of 7 thousand tons was going along the channel. As a result of the wind-driven surge of sea water in the area and the impact of drifting ice, the bulk carrier was moved to a distance of more than 10 km from the fairway of the Volga-Caspian Channel. The icebreakers serving the Channel could not help the bulk carrier. The small-sitting tugboat, which was sent to the rescue, did not have enough strength to pull the bulk carrier aground (Figure 9). After the end of the surge wave and the freezing of the ice, the "Baku" bulk carrier was stuck in the shallow water of the North Caspian for a long time.

Figure 9. The cargo ship "Baku" in shallow water on February 18, 1981.
(Photo by P.I. Bukharitsin)

In those years, in order to facilitate carrying out the maritime operations, attempts were made to artificially crack ice in the Volga-Caspian and Ural-Caspian shipping canals. However, these measures did not give positive results, as the broken ice was shifted to the offshore part of the canals, where the flow velocity decreased, and the ice floes began to clog their channels, creating insurmountable obstacles for ships. In addition, frequent winds of the eastern and southeastern directions tore off and brought out new ice from the sea, which completely blocked the passage of ships and icebreakers into the sea for a long time. Thus, the practice of artificial ice breaking with the help of icebreakers in canals and shallow waters of the Northern Caspian had to be abandoned. Destruction and ignition of the underwater gas pipeline. During the spring flood on the sea reach of the Volga River (Astrakhan Region), the watercourse washed away the poorly deepened and fixed pipeline on the river bottom. The gas pipe appeared to be suspended in a powerful stream of water and burst at the junction. Gas began to gush under pressure. At this moment, a hydrofoil boat was passing by and a spark flying out of the exhaust pipe of this vessel ignited an explosive gas mixture. There was a powerful explosion, as a result of which the ship was thrown out on the bank by wave. Fortunately, people on the ship were not injured. The residents of the neighboring village of Rechnoye were also lucky: the wind blew in the opposite direction from the village, and there was no fire on the shore. Despite the fact that the gas pipeline was quickly blocked on both sides, the gas remaining in the pipe was burning out for many hours (Figure 10).

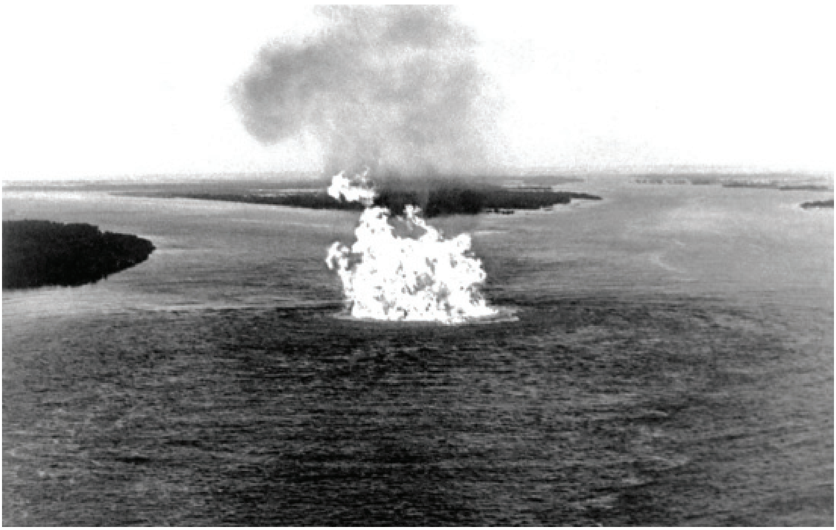

Figure 10. Fire gas pipeline on the Volga River in the area of the village of Rechnoye.
(Photo by P. Tsikunov)

DISCUSSION

With the rapid growth of oil and gas extraction works and the increase of their impact on the environment, there is a need to justify new technical approaches that ensure reliable forecasts of the immediate and long-term consequences of the interaction of natural and production systems. In geoecological studies of oil and gas development in the Caspian Sea, it seems to us timely to apply the approach that integrates geological and geographical knowledge and thus contributes to their mutual enrichment. The main aspects of such studies of oil and gas production in the Caspian are shown in the table.

Table

Parameters of hazardous natural processes in the zones of development of oil and gas deposits of the Caspian Sea

Objects of production and transport	Disasters arising under the influence of natural factors:	
	The eruption of fluid	Storm surges and ice drift
Stationary oil platform on the coast and at sea	Ignition and complete destruction of the facility	Wind-driven flooding and wave destruction of the object; blockage and partial destruction of the object by ice mass
Floating offshore oil platform	Fire, complete destruction and sinking of the object	Wind-driven flooding, wave destruction and sinking of an object; destruction and sinking of the object by drifting ice
Bottom pipeline	Ignition and complete destruction of the facility	Destruction of an object by the underwater part of ice ridges, as well as its probable ignition
Marine vessel, in particular, oil and gas loading	Inflammation, complete destruction and sinking of the object	Moving of an object in shallow waters under the conditions of a surge wave; destruction and sinking of an object in a big wave; destruction and sinking of an object by drifting ice
Costal and marine hydrotechnical construction: piers, breakwalls, dams, bundwalls	Fire, complete or partial destruction of the object	Destruction and sinking of an object; destruction of communications and equipment located at the facility

Source: compiled by the authors.

The table shows that, hazardous hydrometeorological processes compared with geological ones represent a wider range of threats to offshore oil and gas production. But, on the other hand, eruptions and ignition of fluids occur, as a rule, very unexpectedly and are accompanied by destructive explosions and proceed rapidly. Therefore, it is customary to regard the prediction of dangerous exogenous-geological processes within the shelf sections of hydrocarbon exploration or production as a more popular scientific and practical task. In our opinion, an equally serious approach to organizing and conducting research on hazardous processes of both geological and hydrometeorological genesis is required.

CONCLUSIONS AND RECOMMENDATIONS

The existing research experience and instrumental observations of the development of oil and gas deposits in the Caspian Sea water area convince us of the need to implement a parametric approach to geographical analysis and to predict the impact of hazardous natural processes on such developments. On the one hand, it is necessary to significantly expand the front of scientific research aimed at preventing explosions and fires from gushing fluids in the oil and gas fields, often leading to destruction of drilling rigs and stationary oil platforms on the coast and at sea, as well as to sinking of floating oil platforms in the deep zone of the Caspian shelf.

On the other hand, it is required comprehensive studies of the laws and features of the occurrence of storm surges in the Caspian Sea and the catastrophic drifts of ridged ice caused by them which leads to the destruction and sinking of various objects of oil and gas field activity: stationary and floating oil platforms, oil and gas vessels, bottom pipelines and other coastal and marine hydrotechnical facilities and structures.

The results of our study allow us to formulate a number of most common practical tasks for overcoming, or at least mitigating, the danger of catastrophes, on the one hand, of a geological and, on the other hand, hydrometeorological nature:

– organization and implementation of satellite monitoring of the appearance of oil stains on the surface of the Caspian Sea;

– improving the reliability of scientific forecasts of accidental displacements and sudden releases of formation fluids in offshore oil and gas fields;

– development of the scientific basis for predicting and preventing disasters caused by storm movements in winter in the south-western and southern directions of the ice masses of the North Caspian;

– ecological and economic justification of transportation routes and the use of ports for transshipment of oil and gas products in the North and Middle Caspian, taking into account the threat of catastrophic effects of drifting ice.

ACKNOWLEDGEMENTS

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ANALYSIS OF CLIMATIC CONDITIONS DURING THE PAST 24TH CYCLE OF SOLAR ACTIVITY AND THEIR MOST LIKELY CHANGES DURING THE NEXT 25 AND 26TH CYCLES ON THE LOWER VOLGA AND IN THE NORTHERN PART OF THE CASPIAN SEA [13]

ABSTRACT

The main regularities and dependences of the Earth's climate and its individual regions on the cycles of solar activity known today are used. A description is given of the expected variability and specifics of the long-term characteristics of the hydrological and thermal regimes of the lower Volga and the northern part of the Caspian Sea for the previous periods, the period of the 24th cycle and the conditions of the upcoming 25th and subsequent 26th cycles of solar activity.

KEYWORDS: solar activity, climate cycles, temperature, climate forecast

SOLAR ACTIVITY CYCLES

Solar activity is the regular occurrence of characteristic formations in the solar atmosphere: sunspots, torches in the photosphere, floccule, and flares in the chromosphere, prominences in the corona. The areas where these phenomena are observed together are called centers of solar activity. In solar activity (growth and decline in the number of centers of solar activity, as well as their power), there is an approximately 11-year periodicity (cycles of solar activity, Figure 1). Solar activity affects many earthly processes.

The influence of the cyclical processes of solar activity on the Earth's climate was established more than two centuries ago and is now not in dispute by anyone.

Changes in solar activity are cyclical in nature. To date, 11-year, 22-year, 80-year, 190-year solar activity cycles have been identified:

- 11-year cycles (Schwabe-Wolf);
- 22-year cycles (Hoyle);
- "secular" cycles (80–90 years);
- 190-year cycles (indiction).

[13] Analysis of climatic conditions during the past 24-th cycle of solar activity and their most likely changes during the next 25 and 26-th cycles on the lower Volga and in the northern part of the Caspian Sea // Piter I. Bukharitsin, Alexandr N. Andreev, Andrew P. Bukharitsin // ISBN 978-5-905695-56-8. UDC [551.461.24:523.98] (262.81). International Conference "Scientific research of the SCO countries: synergy and integration" Part 1: Participants' reports in English. May 14, 2020. Beijing, PRC. Beijing, China 2020. – C. 142-158.

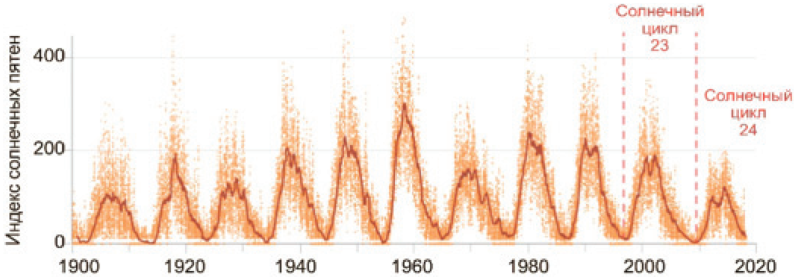

Figure 1. Quasi-11-year cycles of solar activity (Schwabe-Wolf cycles)

11-year cycles (Schwabe – Wolf). To characterize solar activity, in 1849, the director of the Zurich Observatory R. Wolf proposed a conventional unit (Wolf number) – the number of sunspots (Table 1). The connection of 11-year cycles with hydrometeorological phenomena on Earth was established. So, the most severe floods in St. Petersburg occur at the beginning of the ascending branch of the solar cycles with a delay of one year after the minimum (1824, 1924, 1955).

22-year cycles (Hoyle). Upon transition from one 11-year cycle to another, the polarity of the head and tail sunspots in each hemisphere changes. This allowed Hoyle to distinguish 22-year cycles, each of which consists of even and odd 11-year cycles.

"Secular" cycles. A.P. Ghansky singled out 80-year cycles of solar activity, which were called "centuries". In 1939, Gleisberg calculated the duration of secular cycles at about 78 years. In 1956 he specified – 78,8 years. The existence of "secular" cycles was confirmed by M.N. Gnevyshev [1].

190-year cycles ("indiction"). In 1948 L.L. Predtechensky established a cycle of solar activity lasting 190 years, which was called "indiction" – returning. According to Anderson's calculations, indiction consists of two half-periods: 88 and 81 years, a total of 169 years. According to the calculations of D.A. Bonov, taking into account the magnetic properties of 11-year cycles, indiction consists of eight 22-year cycles and lasts 176 years. Analysis of the temperature regime in Astrakhan for the period from 1836 to 2016 is in good agreement with the calculations of D.A. Bonov [2].

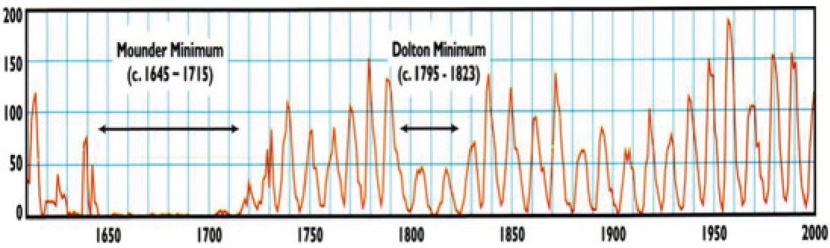

Figure 2. In the optical range, the indicator of solar activity is the average number of spots

In the second half of the XVI century, a general cooling (Little Ice Age) was observed on Earth (Figure 2).

The influence of solar activity on climatic characteristics is regional in nature, and is manifested in the strengthening of atmospheric processes in some regions and their weakening in others. Climate change along the coast and the waters of the North Caspian Sea are unidirectional. Thus, the temperature regime according to the data of the Astrakhan, Tyuleniy, Kulaly, Ganyushkino, Atyrau, Peshnoy, Fort-Shevchenko MSs changes simultaneously and in phase in 1938–2003. Periods of sharp changes in air temperature occur simultaneously and have one trend – increase or decrease [3].

Having data on air temperature observations from the Astrakhan MS since 1836, it is possible to identify the features of the temperature regime from the 8th to the 23rd eleven-year solar activity cycle and extend them to the entire North Caspian region (Figure 3).

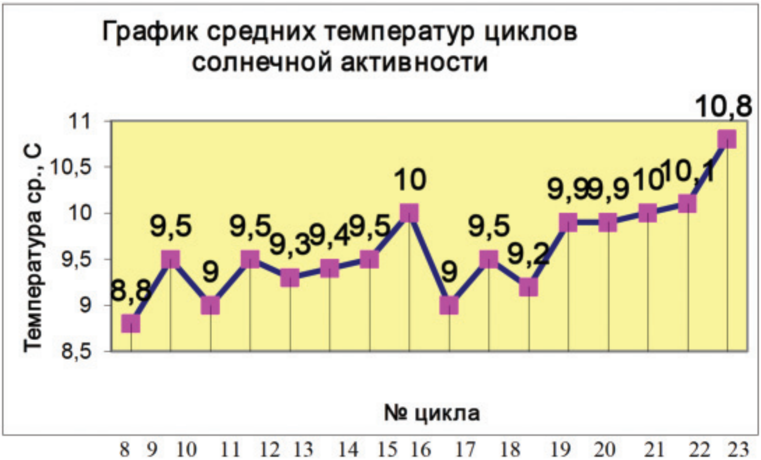

Figure 3. Features of the temperature regime from the 8th to the 23rd eleven-year cycle of solar activity

The past, 24th even eleven-year cycle of solar activity began in December 2008 and lasted until mid-2019. The total cycle duration was 10,8 ± 0,7 years. The main maximum of solar activity in the first half of 2011. The maximum of 5–6 summer cycles fell at the end of 2009 – beginning of 2010 and the end of 2014 – beginning of 2015.

The decrease in atmospheric pressure in the polar regions, characteristic of even 11-year cycles, during periods of increasing solar activity, as a rule, leads to a shift in the center of the Arctic anticyclone to the northeast. Atlantic cyclones that form in moist sea air and pass north of the usual, which, in general, leads to a decrease in precipitation in the Volga and Kama basins and a decrease in the annual flow of the Volga River in the Caspian Sea.

SUNSPOTS AND EARTH'S CLIMATE CYCLES

On Earth, there are relatively short (approximately 10-year) cycles of climatic fluctuations, which approximately coincide with the cycles of activity of the Sun. Can they affect the weather?

The cycles in temperature changes approximately coincide with the cycles of solar activity. However, the peaks of solar activity account for both the warmest (mostly) and the coldest years (Figure 4).

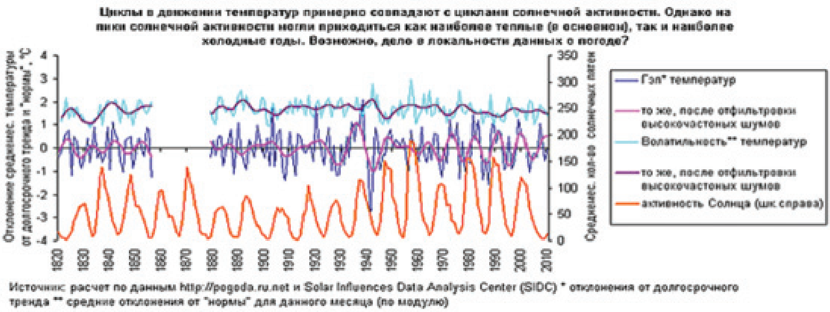

Figure 4. The relationship of temperature changes with cycles of solar activity

Table 1

Changes in solar activity (W) from 1755 to 2018 (in the numerator, years, in the denominator of the Wolf number W)

1	1755 10	1756 10	1757 32	1758 48	1759 54	1760 63	1761 86	1762 61	1763 45	1764 36	1765 21	1764 11		
2	1767 38	1768 70	1769 106	1770 82	1771 82	1772 66	1773 35	1774 31	1775 7					
3	1776 20	1777 92	1778 154	1779 126	1780 85	1781 68	1782 38	1783 23	1784 10					
4	17S5 24	1786 83	1787 132	1788 131	1789 118	1790 90	1791 67	1792 60	1793 47	1794 41	1795 21	1796 16	1797 6	1798 1
5	1799 9	1800 14	1801 34	1802 44	1803 43	1804 47	1805 42	1806 28	1807 10	1808 8	1809 2	1810 0		
6	1811 1	1S12 5	1813 12	1814 14	1815 35	1816 46	1817 41	1818 30	1819 24	1820 16	1821 7	1822 4	1823 2	
7	1824 8	1825 7	1826 36	1827 50	1828 62	1829 67	1830 71	1831 48	1832 27	1833 8				

The end of the Table 1

8	1834 13	1835 57	1836 121	1837 138	1838 103	1839 86	1840 63	1841 37	1842 24	1843 11				
9	1844 15	1845 40	1846 61	1847 98	1848 125	1849 96	1850 66	1851 64	1852 54	1853 39	1854 21	1855 7	1856 4	
10	1857 23	1858 55	1859 94	1860 96	1861 77	1862 59	1863 44	1864 47	1865 30	1866 16	1857 7			
U	1868 37	1869 74	1870 139	1871 111	1872 102	1873 66	1874 45	1875 17	1876 11	1877 12	1878 3			
12	1879 6	1880 32	1881 45	1882 60	1883 64	1884 63	1885 52	1886 25	1887 13	1888 7	1889 6			
13	1890 7	1891 36	1892 73	1893 85	1894 78	1895 64	1896 42	1897 26	1898 27	1899 12	1900 9	1901 I		
14	1902 5	1903 24	1904 42	1905 63	1906 54	1907 62	1908 42	1909 44	1910 19	1911 6	1912 4	1913 1		
15	1914 10	1915 47	1916 57	1917 107	1918 81	1919 64	1920 38	1921 26	1922 14	1923 6				
16	1924 17	1925 44	1926 64	1927 69	1928 78	1929 65	1930 36	1931 21	1932 11	1933 6				
17	1934 9	1935 36	1936 BO	1937 114	1938 110	1939 88	1940 68	1941 47	1942 31	1943 16	1944 10			
18	1945 33	1946 92	1947 151	1948 136	1949 135	1950 80	1951 *69*	1952 31	1953 14	1954 4				
19	1955 38	1956 142	1957 190	1958 185	1959 159	1960 112	1961 54	1962 37	1963 28	1964 15				
20	1965 15	1966 117	1967 94	1968 106	1969 105	1970 104	1971 66	1972 69	1973 38	1974 34	1975 15	1976 1		
21	1977 27	1978 92	1979 155	1980 155	1981 140	1982 116	1983 66	1984 46	1985 18	1986 13				
22	1987 29	1988 100	1989 157	1990 143	1991 146	1992 94	1993 54	1994 30	1995 15	1996 10				
23	1997 21	1998 64	1999 93	2000 120	2001 111	2002 106	2003 74	2004 42	2005 20	2006 15	2007 8			
24	2008 4	2009 27	2010 77	2011 129	2012 145	2013 137	2014 75	2015 42	2016 15	2017 14	2018 4			

Примечание «шала Вольфа в 24-м цикле солнечной активности прогностические. Жёлтый фон – голы с пиковыми (максимальными) значениями солнечной активности. Синий фон – годы с минимально низкой солнечной активностью (депрессивные).

CLIMATIC CHANGES DURING THE 24TH CYCLE AND THEIR CONSEQUENCES

Such significant predicted changes in climatic and hydrological conditions, of course, negatively affected the activities of all, without exception, sectors of the national economy, not only in Astrakhan, the Astrakhan Oblast, but also the entire North Caspian region. This led to significant additional material costs both in the warm and cold seasons of the period under consideration.

In the North Caspian region, the anticyclonicity of the climate increased under the influence of the crest of the Azores and Siberian anticyclones. The weather has become drier. Rainfall decreased. The continental Arctic air mass in which the Siberian anticyclone is formed, as a result of intense radiation cooling in the winter season, determined sharp drops in air temperature.

An increase in the meridional form of atmospheric circulation during periods of maximum solar activity led to an even greater decrease in air temperature in the winter season due to the invasion of Arctic air along the normal polar and ultra-polar axes. This mainly affected the eastern part of the Northern Caspian.

The average annual air temperature in the 24th cycle was about 9 °C, which is 0,69 °C lower than the long-term norm and 1,8 °C lower than in the 23rd cycle (1996–2007). The decrease in average annual temperature was due to a sharp decrease in the temperature of the cold season of the year (November-March) to –3,0–3,5 °C, which is 0,7–1,2 °C lower than normal and 3,0–3,5 °C lower, 1996 2007.

Thus, the 24th even eleven-year cycle of solar activity in the Astrakhan Oblast and the entire Northern Caspian was characterized by arid summers with little rainfall, repeatability of rather cold winters and strong east winds. The general decrease in precipitation in the Volga-Kama basin led to a decrease in the annual flow of the Volga River, to low spring floods, a decrease to critical depths in the summer and winter low-water periods and a general decrease in the level of the Caspian Sea [4, 5].

Strengthening the continental climate of the region affected agriculture, water transport, and affected the fishing industry. In the summer months there was an intensive flowering of water in the reservoirs of the Volga-Akhtuba floodplain and the Volga delta. Due to lack of water, there was a massive drying out of small and medium-sized watercourses in the floodplain and the Volga delta.

Particularly susceptible to this were the water bodies of the Western steppe ilmeni region. It required the implementation of additional volumes of dredging, land reclamation, reconstruction of many existing coastal marine and river hydraulic structures and facilities. The expenditures of the housing and communal complex for providing water to the population, especially during the summer-autumn low-water period, and for heating residential, office and industrial premises in cold seasons increased. Consumption of electric and thermal energy, various types of fuel increased significantly.

Lowering of the level of the Caspian Sea primarily affected its shallow, northern part. In the summer, hot seasons, this led to intense heating and evaporation of water from the vast shallow waters of the Northern Caspian, an increase in the temperature of sea water to dangerous values, and the appearance of extensive zones with hypoxia.

The frequency and intensity of hazardous water drives increased, which led to massive downtime of vessels in the marine part of the Volga-Caspian maritime shipping canal, especially in winter, in the presence of drifting ice [6]. The recurrence of cold and warm winters over a 24-cycle solar activity is shown in the graph (Figure 5).

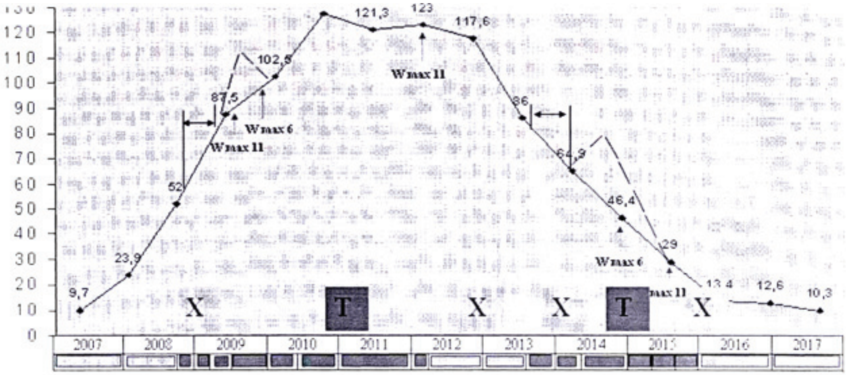

Figure 5. 24th cycle of solar activity

ANALYSIS OF LONG-TERM TEMPERATURE CONDITIONS (1836–2016) AND PRELIMINARY CLIMATE FORECAST FOR 25TH AND 26TH SOLAR CYCLES

Climatologists have been divided into two groups

Some believe that a global warming regime has been established on the globe. The global warming trend is irreversible and is determined by anthropogenic factors. It is proposed to take urgent measures to drastically reduce industrial gas emissions into the atmosphere in order to avoid a sharp warming of the climate and a catastrophic increase in sea level.

Others believe that changes in the temperature regime are cyclical in nature and are determined by the cyclical nature of the processes of solar activity and the change in the angular velocity of the Earth's rotation. It is assumed that solar activity has entered a phase of sharp decline. Starting around 2030, the beginning of the Maunder phase (almost complete absence of sunspots) and the associated new small ice age is predicted.

Analyzing the temperature regime of Astrakhan (regular instrumental observations since 1836) we come to an unambiguous conclusion about the cyclical nature of its changes associated with natural causes.

Cyclical nature of multi-year air temperature

The official position of WMO is this: global warming is the result of the greenhouse effect of increased CO_2 emissions. This is substantiated in the third report of the International Panel on Climate Change (IPCC). However, in recent years, an alternative version has begun to take shape. So A.G. Egorov (2005) believes that the potential for explaining climate change is far from being fully realized, proceeding from the inherent cyclical nature that functions without any human intervention [7]. In the natural variability of the surface atmosphere, there are circulating mechanisms, based on which climate changes can be described without the intervention of anthropogenic factors. One of the reasons for the natural cyclical nature of climate change, the author believes, are changes in solar activity.

In the work of E.A. Kasatkina et al. [8] already posed a statement: At present, there is no doubt that solar activity plays a significant role in global climate change. As a rule, manifestations of solar activity are associated with the appearance of solar cycles with periods of 11, 22, 33 and 88–98 years.

A.I. Ol [9] provides evidence that the 22-year periodicity of changes in meteorological elements is characteristic of many regions of the globe.

Z.M. Gudkovich et al. [10] using the example of changes in the average annual air temperature in the latitudinal zone 17,5–87,5 nl. for the period of 1579–1978 show that for 400 years the air temperature in the Northern Hemisphere experienced cyclic fluctuations. These fluctuations were global in nature and were determined by 11 and 22-year cycles of solar activity.

As an alternative hypothesis to the anthropogenic factor O.A. Anisimov et al. [11] believe that the influence of natural periodicities can be considered: from changes in the parameters of the planetary orbit and the cyclicity in the intensity of solar radiation to the frequency of volcanic eruptions, etc.

Using the example of observations of air temperature in Astrakhan for the period 1836–2016, we will try to show that an alternative to anthropogenic theory may be taking place.

The long-term regime of air temperature has a pronounced cyclic character. Periods of elevated air temperature alternate with colder ones. This is characteristic not only for the Astrakhan region, but also for the whole of Europe.

According to meteorological observations in Europe, the following was observed:

- the coldest periods:1746–1756, 1833–1843, 1923–1933.
- moderately cold periods: 1766–1775, 1855–1867, 1944–1954.
- the warmest periods: 1823-1833, 1913–1923, 1996–2007.
- moderately warm periods: 1810–1823, 1902–1913, 1986–1996.

Cold and warm periods revealed by observations in Europe are in good agreement with 11-year cycles of solar activity and are confirmed by observational data in Astrakhan (Table 2).

Table 2

Average temperatures of cold and warm periods in Astrakhan

Period.	Duration.	JV« of 11-year cycle.	Average cycle temperature
Cold	1746–1756	0	–
	1833–1843	8	8,8
	1923–1933	16	9,0
Moderately cold	1766–1775	2	–
	1855–1867	10	9,0
	1944–1954	18	9,2
Warm	1823–1833	7	–
	1913–1923	15	10,0
	1996–2007	23	10,8
Moderately warm	1810–1823	6	–
	1902–1913	14	9,5
	1986–1996	22	10,2

The coldest are even 11-year cycles, the warmest are odd. The cyclicity, of the cold periods is 89 years, warm – 88 years.

Thus, the cyclical nature of the cold and warm periods, both in Europe and in the Astrakhan region, in particular, corresponds to the "secular" cycles of solar activity calculated by D.A. Bonov.

FEATURES OF THE TEMPERATURE REGIME OF SOLAR CYCLES

Having data on observations of air temperature since 1836, it is possible to analyze the temperature regime during VIII–XXIV eleven-year cycles. Analysis of the data in these tables allows us to draw the following conclusions:

– we believe that the secular cycles of solar activity consist of eight 11-year cycles: VIII-XV and XVI–XXIII or four 22-year cycles, which confirms the calculations of D.A. Bonov. The duration of the first secular cycle is 91 years, of the second – 84 years;

– The indicated secular cycles are half-periods of the 190-year cycle (indiction). The duration of "indiction" is 175 years (according to Bonov's calculations – 176 years);

– the average air temperature of the solar activity cycles – "indiction", "secular", 22-year and 11-year is 9,69 °C (average annual air temperature);

– the average air temperature of the 22-year cycles (Hoyle), which make up the secular cycle, rises from the first to the fourth, by an average of 0,39 °C (9,15–9,25–9,35–9,75 °C in the first secular cycle and 9,25–9,55–9,90–10,45 °C in the second;

– the average air temperature of even (odd) 11-year cycles, as a part of a century long cycle, rises from the first to the fourth, by an average of 0,3 °C;

– the initial (even) 11-year cycle has the lowest air temperature of all eight 11-year cycles that make up the secular (8,8 °C in the first secular cycle and 9,0 °C in the second,);

– the final (odd) 11-year cycle has the highest air temperature of all eight 11-year cycles that make up the secular (10,0 °C in the first secular cycle and 10,8 °C in the second);

– the average air temperature of an even 11-year cycle is always lower than that of an odd one in pairs that make up the 22-year cycle (this also applies to the phase of decline in the activity of 11-year cycles);

– the average air temperature of any 11-year or 22-year cycles of the initial "secular" cycle, as part of the "indiction", is always lower than the corresponding 11 and 22-year cycles of the final "secular" cycle;

– the indicated features of the temperature regime of 11-year and 22-year solar cycles extend to the average air temperatures of years (as part of these cycles), the cold seasons of the year (November-March), as well as the months of February, March and April;

– the average temperature of the cold season of the year rises from 1 to 4 even (odd) 11-year cycles as part of the "secular";

– the average air temperatures of December, February, March and April of the months of the even 11-year cycle are colder than the odd ones in the pair making up the Hoyle cycle.

The binary system in the structure of solar cycles from 11-year to "indiction" is clearly visible:

- 11-year cycle consists of two 5,5–6,0 year.
- 22-year cycle consists of two 11-year.
- two 22-year cycles make up the half-cycle of the "secular" cycle.
- "secular" cycle consists of two half-periods.
- "indiction" consists of two "secular" cycles, etc.

Figure 6 shows the long-term course of average air temperatures of 11-year.

An analysis of the temperature regime for the period from 1836 to 2016 shows: In the multi-year regime of air temperature, a pronounced cyclicity is observed. This cyclicity is in good agreement with changes in solar activity.

Changes in solar activity lead to changes in the prevailing types of atmospheric circulation and, as a result, to changes in the temperature regime.

So the average air temperature (meteorological year, cold season) in even 11-year cycles is always lower than in odd ones – in the pair that makes up the Hoyle cycle.

In the "secular" cycle, consisting of eight 11-year cycles (Wolf cycles), the average temperature rises from the first to the fourth, both even and odd cycles.

With the beginning of the next "secular" cycle, the average temperature of the first Wolf cycle drops sharply, and then begins to rise.

The same pattern applies to Hoyle cycles (22-year).

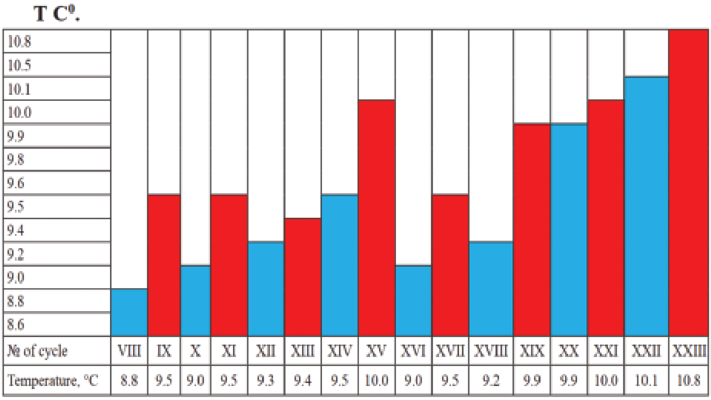

Figure 6. Schedule of distribution of average annual air temperatures (°C) over 11-year cycles of solar activity

The sectoral structure of the interplanetary magnetic field, due to the presence of unipolar magnetic fields on the Sun, predominates in even 11-year cycles of extremely cold years (76 %), and in odd extremely warm years (67 %).

In addition, the features of the temperature regime of the phases of activity of 11-year cycles were revealed.

The increase in the average annual air temperature observed in the city of Astrakhan since the 70s of the XX century (growth rate of 0,2 °C/10 years) is due to an increase in the average air temperatures of the cold season of the year and spring, with almost the same average temperature of the warm season and autumn.

Along with the increase in average annual air temperature, the temperature regime redistributed throughout the year: spring (April) became warmer than autumn (October), the average March temperature increased from –0,4 °C to +0,4 °C, and the average May temperature decreased (which led to an increase in the frequency of frosts in the first decade of May).

The XXIII eleven-year solar cycle (1996–2009) became the warmest for all years of observations – the average annual air temperature +10,8 °C (at a rate of +9,6 °C), the average temperature of the cold season –0,2 °C (at normal –2,3 °C).

Probably the peak of the next increase in air temperature associated with changes in solar activity has been passed. This is confirmed by changes in the humidification mode. A sharp increase in the annual precipitation observed in 1990–2000 was replaced by a decrease.

Preliminary forecast of the 25th solar cycle

Scientists entrusted with predicting the activity of the Sun over the next 11-year solar cycle, say that it is likely to be weak, very similar to the current one.

The current 24th solar cycle is decreasing and is projected to reach a solar minimum – the period when the Sun is least active – not earlier than July 2019, and no later than September 2020. In support of this theory, an analysis of the severity of winters that we spend and characterizing the last three winter seasons from 2017 to 2020 in the lower Volga and the northern part of the Caspian Sea showed that the severity of winters decreased with a decrease in FDD.

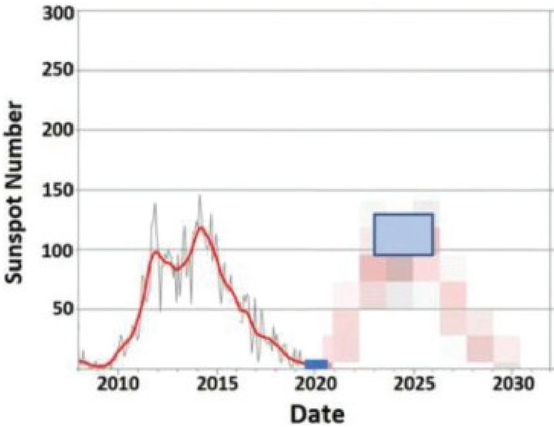

Figure 7. Forecast of the 25th solar cycle

Experts from the 25th Solar Cycle Prediction Group say the new solar cycle may have a slow start. The period of greatest solar activity (solar maximum) is expected between 2023 and 2026 with a sunspot range of 95 to 130. This is well below the average number of sunspots, which usually ranges from 140 to 220 per solar cycle. Experts are confident that the upcoming cycle should break the tendency to weakening solar activity observed over the past four cycles. "We expect the 25th solar cycle to be very similar to the 24th: another rather weak cycle, which is preceded by a long, deep minimum", says group co-chair Lisa Upton, Doctor of Philosophical Sciences and solar physicist at Space Systems Research Corporation (Figure 7).

Expected climatic conditions for the 25th solar cycle (from 2021–2022 to 2032–2033)

The first two years will be colder than normal. The sum of the average temperatures of the calendar winter will be below –20,0 °C. Further, to the peak of the activity of the cycle, the increase in the average annual temperature will be higher than the norm (10,5–11,0 °C) and by the end of the cycle again a steady decrease in temperature. Fluctuations in average temperatures will be determined by their fluctuations in the period November-March. At the beginning and end of the cycle, the early establishment of ice cover in the lower Volga and in the Northern Caspian.

Expected climatic conditions for the 26th solar cycle (2023–2033 to 2043–2044)

The beginning of the Maunder phase and the onset of the little ice age. The influence of solar activity on climatic characteristics is regional in nature, strengthening atmospheric processes in some regions and weakening in others.

Climate change along the coast and the waters of the North Caspian Sea are unidirectional. Thus, the temperature regime according to the data of the Astrakhan, Tyuleniy, Kulaly, Ganyushkino, Atyrau, Peshnoy, Fort-Shevchenko MSs changes simultaneously and in phase in 1938–2003. Periods of sharp changes in air temperature occur simultaneously and have the same trend – increase or decrease.

Given the correlation coefficient, the expected climatic conditions for Astrakhan can be extended to the entire northern coast and the water area of the Northern Caspian. The predominant synoptic process will be the Asian (Siberian) anticyclone or its crest, which will be accompanied by an extremely low amount of precipitation, long and strong winds of the eastern quarter. In the warm seasons, dust storms and dry winds. Severe ice conditions in the Northern Caspian in winter from December to March.

CONCLUSIONS AND RECOMMENDATIONS

Strengthening the continental climate of the region will affect all sectors of the economy. An additional amount of dredging, reclamation, and, possibly, reconstruction of many existing coastal marine and river hydraulic structures and facilities will be required. Housing and communal services will increase expenses for providing water to the population, especially during the summer-autumn low water season, and for heating residential, office and industrial premises in cold seasons. The consumption of electric and thermal energy and various types of fuel will increase significantly.

Lowering the level of the Caspian Sea will primarily affect its shallow, northern part. In the summer, hot seasons, this will lead to intensive heating and evaporation of water from the vast shallow waters of the Northern Caspian, an increase in the temperature and salinity of sea water to dangerous values, and the emergence of extensive zones with hypoxia. In the cold seasons, as a result of the reduced heat capacity of shallow water under the influence of low temperatures and intense wave mixing in the initial period of ice formation, a thick ice cover will form in the Northern Caspian, whose thickness will reach its maximum, long-term values by the middle of winter. In connection with the decline in the level of the Caspian and the decrease in depths in the shallow northern part of the sea, the duration of the ice period will increase, the average thickness of thermal ice will increase, and the intensity of ice hummocking will increase. Cohesive floating ice, carried by the wind and currents into the deep sea, the middle part of the sea and drifting along the coast to the south, will pose a special threat. The bottom of the sea almost everywhere in the entire Northern Caspian will be exposed to the plowing effects of heavy drifting ice. The frequency and intensity of hazardous water drives will increase, which will pose a serious threat to the safety of navigation, especially in the marine part of the Volga-Caspian maritime shipping canal, leading to mass death of fish, especially in the initial period of ice formation in coastal shallow waters.Development of the “North Caspian Square” license area of the “Caspian Oil Company” LLC in shallow and extremely shallow waters annually covered by ice, its direct proximity to the protected zone of the Caspian Sea with unique biological resources, lack of technical means for the construction of prospecting and search and exploration wells, transport and towing and rescue vessels of the ice class with low draft is associated with significant geological, industrial, environmental, financial, social, reputational and other risks that must be taken into account by the subsoil user and minimize them when implementing the project in order to increase its effectiveness and profitability.

One should take into account the option of lowering the water level in the Caspian Sea, in which a situation is not excluded when the depth of the sea, even taking into account the construction of approach channels and vast working areas, will not allow an unhindered approach of supply vessels to the artificial islands created for the development of the field.

By the set and significance, the risks of subsoil development in shallow water areas with annual seasonal ice cover, associated with a specially protected natural area, characterized by high bio-productivity and extremely high vulnerability in the event of accidental oil and oil product spills, may be unparalleled [12].

For stable and regular operation of the whole Volga-Caspian water transport complex as a whole during this period, it will be necessary to increase the composition of the icebreaker fleet in the Northern Caspian. It will be necessary to ensure the reliable operation of numerous ferry crossings, the operation of which currently does not stand up to criticism, especially in the ice period. The main problem is the morally obsolete fleet and the extreme deterioration of non-self-propelled ferries that require immediate replacement with new, self-propelled and all-weather, and having the ability to work independently in broken ice [13].

It will require the creation of a specialized system of hydrometeorological support for maritime activities and a service for operational monitoring of the ice situation in the lower Volga and the freezing part of the Northern Caspian (similar to the headquarters of ice operations, as it was during the times of Soviet Union, it worked well). Without such a service, ensuring the rhythmic operation of the water transport complex and navigation in the Caspian will be impossible. The service for operational monitoring of the ice situation will provide companies operating here with timely and reliable information about ice activity in this region, minimizing risks and losses, which in turn will increase economic efficiency and reduce the cost of conducting economic activities in the Caspian region seas.

CONCLUSION

Of course, all of the above is only scientific assumptions based on actual long-term hydrometeorological data and forecasts of colleagues in related fields of knowledge, in particular, in the field of studies of solar-active bonds. Yes, until the technology is perfect, there are many unexplored and undetected factors and relationships. But, unfortunately, there is no other alternative, since at present, and in the foreseeable future, the traditional methods of the hydrometeorological service cannot predict for such long periods. It should be noted that (fortunately or unfortunately) the previously predicted consequences of the influence of the past 24th cycle of solar activity on climatic conditions in the North Caspian region for the period from 2006 to 2017 came true almost completely! As they say: Forewarned is forearmed!

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ICE-GOUGING TOPOGRAPHY OF THE EXPOSED ARAL SEA BED[14]

ABSTRACT

Ice gouging, or scouring, i.e., ice impact on the seabed, is a well-studied phenomenon in high-latitude seas. In the mid-latitudes, it remains one of the major geomorphic processes in freezing seas and large lakes. Research efforts concerning its patterns, drivers and intensity are scarce, and include aerial and geophysical studies of ice scours in the Northern Caspian Sea. This study aims to explain the origin of the recently discovered linear landforms on the exposed former Aral Sea bottom using remotely sensed data. We suggest that they are relict ice gouges, analogous to the modern ice scours of the Northern Caspian, Kara and other seas and lakes, previously studied by side scan sonar (SSS) surveys. Their average dimensions, from 3 to 90 m in width and from hundreds to thousands of meters in length, and spatial distribution were derived from satellite imagery interpretation and structure from motion-processing of UAV (unmanned aerial vehicle) images. Ice scouring features are virtually omnipresent at certain seabed sections, evidencing high ice gouging intensity in mid-latitude climates. Their greatest density is observed in the central part of the former East Aral Sea. The majority of contemporary ice gouges appeared during the rapid Aral Sea level fall between 1980 and the mid-1990s. Since then, the lake has almost completely drained, providing a unique opportunity for direct studies of exposed ice gouges using both in situ and remote-sensing techniques. These data could add to our current understanding of the scales and drivers of ice impact on the bottom of shallow seas and lakes.

KEYWORDS: Aral Sea; ice gouging; bottom topography; ice scours; remote sensing.

INTRODUCTION

Sea ice as a zonal factor is associated with high latitudes and plays an important role in the evolution of the coasts and seabed in polar regions [1–4]. It can execute direct mechanical, thermal, physical and chemical impact on the coasts and bottom [1,5,6]. However, ice can also affect the coasts and bottom of freezing seas and large lakes in mid-latitudes [7–9], in particular, of the Caspian [10–13] and Aral Seas. The most dangerous and impressive process driven by ice is mechanical plowing of bottom ground called ice gouging. It is associated with ice cover movement, ice

[14] Ice-Gouging Topography of the Exposed Aral Sea Bed // Stepan Maznev, Stanislav Ogorodov, Alisa Baranskaya, Aleksey Vergun, Vasiliy Arkhipov, Peter Bukharitsin // Remote Sens. 2019, 11, 113; doi:10.3390/rs11020113. – C. 1-25.

hummocking (ridging) and formation of grounded hummocks (stamukhas) under the influence of hydrometeorological factors and coastal topography [3, 14, 15]. Ice gouging significantly changes bottom topography and can affect engineering facilities, e.g., oil and gas pipelines [13, 16–18].

Studies of ice effect on the seabed in the middle latitudes started back in the 1950s in the Northern Caspian Sea [10]. Soviet researchers described traces of sea ice impact using aerial imagery. Such traces were best seen in shallow zones at depths of 1–3 m in wave-protected inlets [19]. With the onset of modern geophysical methods, further investigations at the Northern Caspian in March 2008 showed ice scours with lengths exceeding several kilometers. The width of single scours reached 5 m; the width of their combs was up to 200 m; the depth of the scours reached 1 m [12]. In North America, J. Grass [7] first described deep ice keels scouring the bottom of Lake Erie down to depths of 25 m, penetrating loose sediments down to approximately 2 m. More studies of the Great Lakes followed [20–22]. In [23], ice conditions during 41 years are compared with extensive statistics on ice scours. Discoveries of ice scours on land were described near lake Ontario [24], where they were possibly made by icebergs, in the sediments of Scarborough Bluffs, Toronto [25,26], and even at Racetrack Playa, California, where they were created by ice-rafting rocks [27].

The present study aims to characterize ice-gouging processes and landforms at the Aral Sea bed, their origin and evolution. The Aral Sea (Figure 1) is a unique site for studies of ice gouging, as most of its bottom is now exposed after a rapid water level decline. Modern remote sensing methods provide an opportunity to detect ice scours on the surface of the former sea bottom, as well as at shallow depths under water (usually not exceeding 3 m). The possibility of direct in situ observations allows detailed studies of the ice gouges' morphology and distribution.

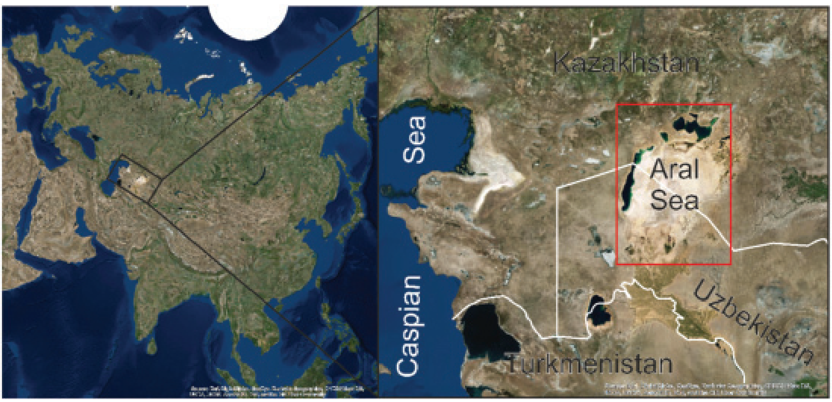


Figure 1. Study area. The red rectangle surrounds the territory of the Aral Sea during its greatest extent in the 20th century

Scours at the exposed bottom of the former Aral Sea were first discovered on aerial photographs in 1990 by B. Smerdov from the Hydrometeorological Institute of Kazakhstan [28]. He made a field description of the landforms and a trial pit and showed that traces on the Aral seabed are up to 8 km long, look like a "comb" and reach 0,4–0,5 m in depth. However, Smerdov rejected the version that such landforms appeared by ice gouging and interpreted them as traces of divine origin or traces of aliens' activity. Detailed academic studies of ice gouging at the bottom of the Aral Sea started very recently [29]; until now, no consistent descriptions and investigations of these landforms were made.

Here, we use high-resolution satellite imagery along with field surveys to characterize ice gouging landforms and reconstruct mechanisms of ice impact on the Aral Sea bottom. We also estimate its main climatic drivers and compare the landforms on the exposed bottom of the Aral Sea to relatively well studied ice gouges of the Caspian Sea and Arctic seas.

SITE DESCRIPTION

The Aral Sea is located in an inland cold desert. The summer is dry and hot; the winter is cold with unstable weather [30, 31]. In November, air temperature in the northern part of the sea drops below zero; the average temperature of January is –11–139 °C. In the southern part of the sea, the average temperature of January is –6–89 °C. The period with negative temperatures lasts for 120–150 days [32]. In winter, when the Siberian Atmospheric Pressure High affects the vast area of the Aral Sea, invasions of cold air masses from the north and northwest provide rapid temperature drops. In warm seasons, when the Siberian High recedes, the South Asian Low affects the region, and winds from eastern directions persist. In March, air temperature quickly rises to +5…+109 °C.

Depths of the Aral Sea at its greatest extent before the 1960s reached 60 m (Figure 2). The bottom topography of its eastern part was extremely flat with a mean inclination of 1–2 ‰ and depths of 10–20 m. The central parts of the North and East Aral Sea are flat wide depressions with former water depths from 20 to 30 m. The greatest depths of up to 65 m were observed in the West Aral Sea, stretching in a narrow patch from the north to the south along its western coast. The steep western underwater slope of the depression is a continuation of the Ustyurt Plateau chink down in the Aral Sea.

Before 1960, water level in the Aral Sea was at the elevation of 53 m a.s.l. (above mean sea level) (Figure 2). In 1961, it started to decline as a result of the flow redistribution of Syr Darya and Amu Darya rivers discharging into it. After extensive water use for irrigation of cotton and rice fields, these rivers could not further sustain the water balance of the Aral Sea, and evaporation exceeded discharge. Consequently, the Aral Sea experienced a fast level drop. In 55 years, the water level lowered by more than 30 m in some locations (Figure 3). Because of the level decrease, in 1986, the lake split into the North and South Aral Seas, which started to retreat separately. In 2007, the South Aral Sea was divided into the West and East Aral Seas (Figures 3 and 4). Today, the water level of the North Aral Sea is at 42 m, the level of the West Aral Sea is at 23,5 m. The level of the East Aral Sea was at 28,5 m, before it dried out completely by 2014 [33–35].

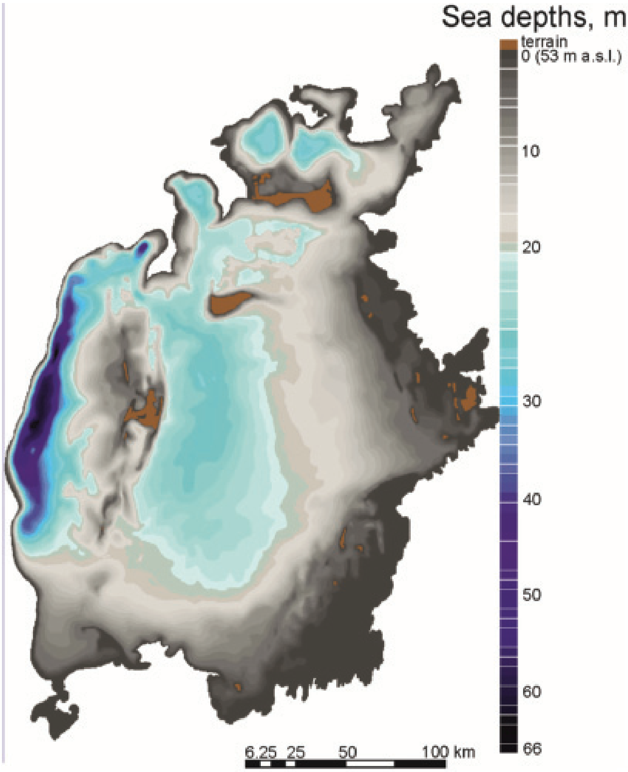


Figure 2. Bathymetric chart of the Aral Sea referenced to a pre-1960 water level (53 m a.s.l.) [36]

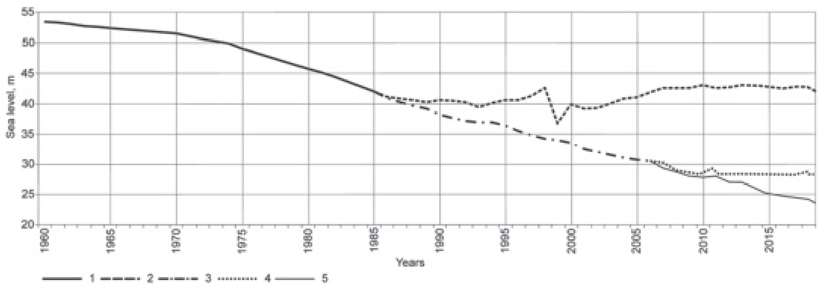
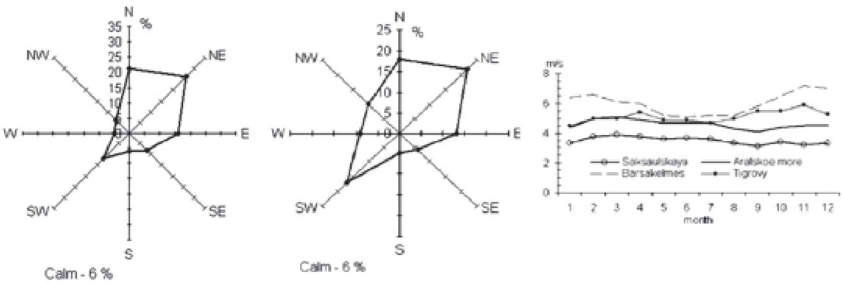


Figure 3. Fluctuations of the Aral Sea level (after [30] – before 1993 and after [33–35]–in 1993–2018):
1 – Aral Sea (1960–1986); 2 – North Aral Sea (1986–2018); 3 – South Aral Sea (1986–2006);
4 – East Aral Sea (2007–2018); 5 – West Aral Sea (2007–2018)

Figure 4. General view of the exposed Aral Sea bottom; key sites of fieldwork are shown by red dots; hydrometeorological stations are shown by blue rectangles; the red line indicates the coastline in 1960 and shows the area where ice scours were deciphered for estimations of their density. Background: ESRI, DigitalGlobe (WorldView-2)

The salinity of the Aral Sea increased significantly as a result of water level decrease. In 1961, the average salinity of the Aral Sea water was about 10 ‰; by 1990, it had increased to 32 ‰. In 2008, the salinity of the Western Aral Sea exceeded 100 ‰, and the Eastern Aral Sea had the salinity of 210 ‰ [37].

Ice conditions of the lake during its high level position in the past were favorable for ice gouging. Before the 1960s, the Aral Sea usually began freezing up in November, reaching its maximum extent in mid-February. Fast ice covered the coastal zone of the sea, reaching 20–30 km in width in the north; open areas were occupied by drifting ice consisting of brash ice and ice fields. Ice thickness ranged from up to 65–70 cm in the north to 35–45 cm in the south. Fast ice was broken up repeatedly by strong winds during the freeze-up, and drifted offshore. Because of strong northeasterly winds (up to 35 % occurrence in the cold period) (Figure 5), rafted ice and hummocky formations were appearing. Northerly and easterly winds pushed the ice to the southern part of the sea, causing its high concentration in the south [38]. Ice was starting to melt in the second half of February and completely disappeared by the end of April [32].



a b c

Figure 5. Frequency of wind directions (%) at the hydrometeorological station (HMS) Aralskoe More (Aral Sea), (a) in February, (b) annual, (c) mean monthly wind velocities (ms-1) [30], locations of HMSs are given in Figure 4

After the water level drop, ice conditions became more severe. Along with the decrease in water area, the Aral Sea froze up faster and several days earlier; ice melting began later and lasted longer [39]. Results of satellite imagery monitoring in 1982–2009 confirm significant changes in the thermal and ice conditions compared to the quasi-undisturbed period before 1961, resulting from shallowing and heat content lowering, along with the decrease in temperatures of the water layer immediately below the ice [40, 41]. Therefore, the climate of the Aral Sea region, similarly to the Northern Caspian region [30], provided favorable conditions for ice scouring of the bottom by hummocks both before and during the water level fall. Strong winds and presence of drifting ice for up to 6 months gives evidence of permanent mass movement of large ice fields, while the presence of relatively vast shallows both before and after the water level fall implies that the keels must have penetrated into the bottom ground causing extensive formation of ice scours (Figure 6).

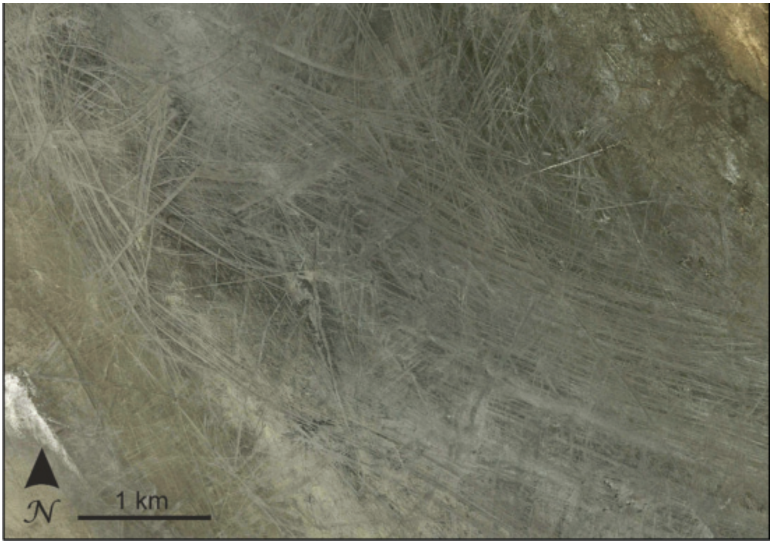


Figure 6. Fragment of WorldView-3 [42] space image showing significant coverage of the former bottom by scours to the west of Barsa-Kelmes Island

MATERIALS AND METHODS

Remote Sensing

For documentation of ice gouging topography on vast territories of the former Aral Sea bottom, high-resolution imagery with significant spatial coverage was required. We analyzed the exposed bottom of both the North and South Aral Seas within the limits of the shoreline of 1960, as well as shallow waters down to 3 m depth, estimating the bottom coverage by scours. A key area in the northeastern part of the East Aral Sea (Figure 4) was subject to more detailed studies with analysis of the morphologic and morphometric parameters of the scours, their directions and distribution.

The whole area of investigations within the shoreline of 1960 (about 50,000 km^2) is comparable to areas of average European countries, e.g., Estonia. Using commercial products such as WorldView or QuickBird for such large areas would immensely increase the cost of investigations. Because our aims did not require the processing of multitemporal data, we used public open source imagery taken not earlier than 2010, when, as we assume, the intensity of ice gouging at the Aral Sea significantly reduced. We used WorldView, QuickBird, Sentinel, IKONOS, and GeoEye images taken from Bing [43], Yandex [44], Google [45] websites and ESRI [42], the combination of which covered the whole study area without clouds, deep water areas, etc. The imagery was georeferenced and interpreted in ArcGIS 10,2 (ESRI Inc., Redlands, CA, USA).

Optical imagery allows ice scours and other forms of ice impact on the bottom to be distinguished due to the difference in spectral reflectance. However, the scours can be both brighter and darker than the background surface, and may have a complicated shape. Therefore, we considered manual selection of the scours to be most reliable. An important step was separating the forms of ice impact on the exposed bottom from other linear objects, above all, erosional landforms, identifiable by their sinuosity or flow marks (typical stream textures), and roads, characterized by fixed width. As a result of the imagery interpretation, we obtained linear shapefiles showing the scours.

In total, we processed 138 scours within the key area in the northeast of the Aral Sea (Figure 4). For each of them, we determined:

- its length as the sum of its straight segments;
- its typical or average width (in case of significant difference between segments, the width of single scours and "combs" was determined);
- its general direction, defined as the direction between the end points or, in case of a complex shape, the direction of the longest segments;
- the order of the scours' appearance in case of their imposition;
- the number of single scours in a comb (in case of multiple gouges).

The obtained data were further statistically processed in Ms Excel. For all parameters, maximum, minimum and average values, standard deviations, and coefficients of variation were calculated. To estimate the bottom coverage by the ice scours and their distribution, areas with similar patterns and a visually similar coverage (n = 46) were selected. Within these areas, small experimental key sites (e.g., 1×1 km) were assigned, where the surface affected by ice gouging was deciphered using polygon ArcGIS shapefiles, and the percentage of land coverage by ice gouges was calculated. These values were extrapolated to larger previously selected areas (n = 22 after merging), and

grouped into intervals reflecting the degree of ice impact, in order to create a scheme of the whole former Aral Sea bed. Such assessment is quantitative and precise for the experimental key sites only; for larger areas it is based on visual similarity and expert opinion, being a qualitative estimation, allowing to reveal general patterns only.

Photogrammetric Field Investigations and Data Processing

During fieldwork conducted in October 2018 in the northeastern part of the East Aral Sea (Polygons 1–5, Figure 4), fragments of ice gouges on the former bottom were shot by an unmanned aerial vehicle (UAV) with subsequent ortho-photo mosaic and digital elevation model (DEM) creation. A DJI Phantom 4 Professional Drone was used [46]; the photographs were taken from the nadir (vertical) viewing direction. Flying missions were planned using the Android application PIX4DCapture [47]. The size of the investigated polygons varied depending on local conditions, generally being several hundred meters (e.g., 500×500 m). The UAV survey took place at a height of 50 or 100 m, depending on the required resolution with traverses along or across the polygon. The shooting was done with an overlap of 60–80 %, allowing to obtain a high-resolution DEM. The shooting frequency was 30 frames per minute. Parameters of the UAV surveys and their accuracy are shown in Table 1.

Table 1

Parameters of the unmanned aerial vehicle (UAV) survey

Survey Height, m	Frame Length, m	Frame Width, m	Resolution, m Per Pixel	Vertical Accuracy, m
100	125	70	0,025	0,04
50	50	30	0,01	0,04

For referencing of the surveys, a network of ground control points (GCPs) was used. The GCPs were 15×20 cm black and white paper markers placed in the corners and center of each polygon. Georeferencing of the GCPs was performed by Javad Maxor GNSS (global navigation satellite system) receivers with an accuracy of about 1 cm in plan and 2 cm in height. One of the GNSS receivers was installed above the main GCP with a survey peg; the rest of the GCPs were referenced by another receiver. Polygons were referenced to each other in a similar way. GNSS receivers were also used for referencing verification level profiles. Polygons and level profiles were referenced to the Kazakhstan Hydrometeorological Services Agency height datum.

Leveling profiles were made to check the accuracy of the resulting DEM. The measurements were conducted with a BOIF AL 120 automatic level with a vertical accuracy of 1 mm. The position of key and typical topographic points was measured to correct distances and elevations. Geomorphological descriptions of the territory were also made; field photographs of the ice-gouging landforms were taken. Trial pits and trenches were made at the polygons with the most prominent scours (polygons 1, 3 and 5). The trenches were up to 7 m long and about 30 cm deep; they were usually made across the scours. Detailed descriptions of the sediments were made, including their color, grain size, mechanical properties, inclusions, etc.

Agisoft PhotoScan software [48] was used to implement the structure from motion (SfM) workflow. Details of the processing parameters and processing times are provided in [49–51]. The algorithm involved identification and matching of features, implementation of bundle adjustment algorithms to estimate the 3D geometry, and a linear similarity transformation to scale and georeference the point cloud and point cloud optimization. In this study, the precise location of the GCPs was identified manually with coordinates taken from GNSS receivers. Finally, implementation of multi-view stereo (MVS) image matching algorithms allowed a dense 3D point cloud to be built. The SfM workflow further generated textured 3D models and ortho-photo mosaics derived from the dense point clouds.

RESULTS

Morphology and Parameters of the Landforms on the Former Aral Sea Bed

Analysis of satellite imagery of the northeastern Aral Sea has shown abundant linear landforms on the former bottom (Figure 7). Their length varies from hundreds of meters to several kilometers, while their width ranges from 3 m to 90 m (15 m on the average) (Table 2). Numerous "combs", consisting of several parallel ice scours (four on the average) potentially made by a large ice hummock were discovered. The scours mostly concentrate at former depths from 15 to 25 m in relation to the 53 m a.s.l. base elevation of the lake level before its fall. They have prevailing ENE-WSW (60–240°) directions; maximum secondary peak of the NNW-SSE (150–330°) oriented scours is present (Figure 8). The rose diagram of the scours shows that the orientation of the most abundant scours (first ENE-WSW peak) coincides with the prevailing winds. These scours were created by the drift of large ice bodies pushed by the most frequent winds. The second NNW-SSE direction does not match the distribution of the most frequent winds; however, it is parallel to the coast and fast ice border of the former Aral Sea. These gouges appeared at locations where the ice fields and hummocks collided with stable fast ice, creating scours parallel to its rim. In this way, the orientation of the described scours is typical for linear landforms created by drifting ice and indicates their ice-gouging origin.

Table 2

Parameters of the ice scours of the northeastern Aral Sea bottom

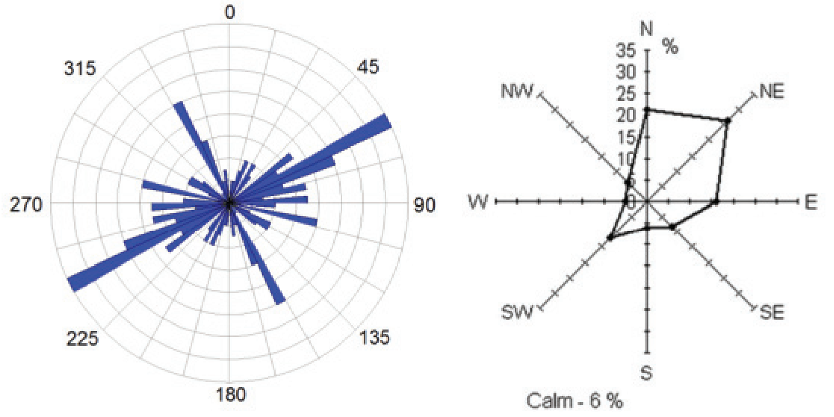
Characteristic	Length, m	Single Scour Width (with Ridges), m	Comb Width, m
Minimum	106	3	13
Maximum	8650	89	386
Average	1302	15	72

About 90 % of the scours documented within the study area (northeastern Aral Sea) are straight; 10 % are curvilinear. Most of the turns are sharp; however, smooth curves are also observed. The presence of both sharp and smooth bends is a typical feature for ice gouging landforms at the bottom of freezing seas, as the winds pushing the ice formations can change their force and direction either abruptly or slowly, depending on the weather conditions.

In locations with intersections of the scours (Figure 9), they are imposed on each other and cut each other. It can be seen in the figure that scour 1 appeared first and scour 2 crossed it later. Scour 3 cuts both of these scours, being the youngest of the three.

Figure 7. Example of imagery interpretation: initial space image (top) and interpretation scheme (bottom). The location of the area is shown as a red dot

The selected landforms cover most of the study area in the northeast of the Aral Sea; they turned out to be clearly distinguishable both in 2D and 3D by remote-sensing data analysis, UAV investigations and field surveys (Figure 10).



a b

Figure 8. Rose diagrams showing the prevailing directions of scours at the northeastern Aral Sea (a); frequency of wind directions (%), for February (b)

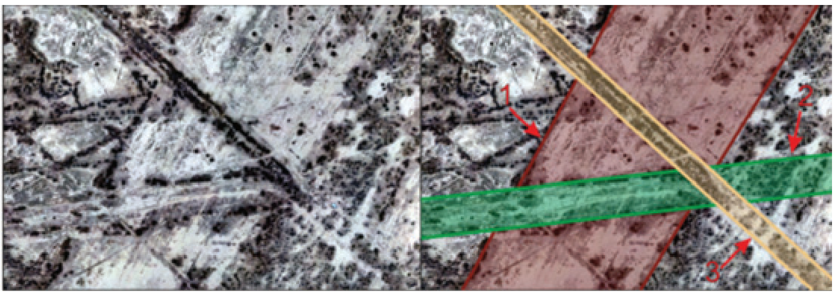


Figure 9. Overlapping of the scours on the Aral Sea bottom from UAV survey (polygon 3). Scour 1 is the oldest, scour 2 is younger, scour 3 is the youngest

The cross-section of a typical scour consists of two sediment ridges (side berms) divided by a depression stretching over its total length (Figure 10 c,d). The depth of the scours varies from 0 to 30 cm, the height of the ridges ranges from 0 to 20 cm, and the total amplitude reaches 50 cm. Field descriptions of the soils in the trial pits and on the surface showed that the ice gouges cut into brownish grey sandy loams (polygon 1), silty loams (polygons 2 and 3) and clayey sands (polygons 4 and 5) with mollusk shells and plant debris. Clayey soils with some sandy particles are typical for the northeastern Aral Sea. For the entire Aral Sea, bottom sediments vary from sands to clays.

Figure 10. View of a model ice scour: (polygon 3): (a) on space imagery (WorldView-3) [42]; (b) on the ortho-photo mosaic (UAV survey); (c) ground view; (d) cross-section taken from a leveling survey. The location of the place where the ground view photo was taken is shown as a red pointer; the red line AB indicates the position of the leveling profile

Investigations of sections in trial pits showed that sediments in the side berms are looser compared to sediments under the depressions, providing evidence of compaction under pressure along the axis accompanied by mellowing of the berms. In some locations, the ice scours have practically no relief and turn out to be just strips of relatively loose or relatively dense sediments, detectable by the resistance of the soils during excavation, despite the same grain size along the whole profile. The strips of looser and denser sediments also differ in soil color. Due to the lack of vegetation and widespread aeolian processes, ice sours have different preservation and disappear through time. In some areas, e.g., near the former Uzun-Kair Island (northeastern Aral), aeolian deposits cover the ice-gouging landforms completely or partially.

At the ends of the scours, where the hummocks presumably broke off from the bottom, distinctive pressure ridges are seen (Figure 11). Similar forms were found in places where the orientation of a gouge changed as the ice formations were drifting pushed by the changing winds and currents. The pressure ridges are mounds of irregular shape up to 30 cm high, up to 3 m in width.

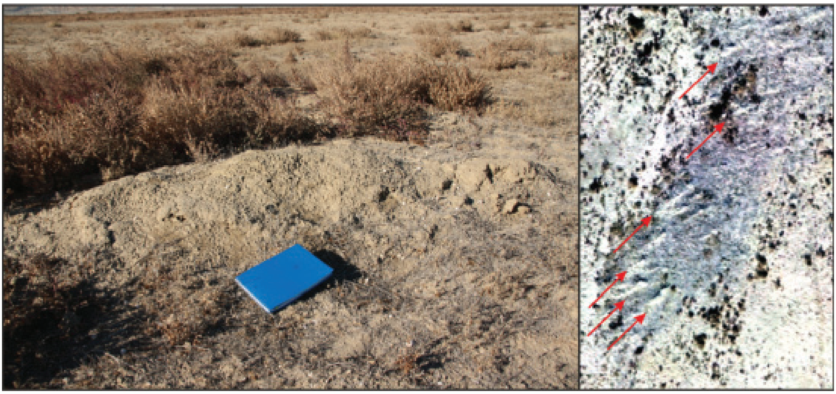


Figure 11. An example of a ground (left) and aerial (right) view of small pressure ridges at polygon 2

The results of the UAV surveys (Figures 12–15) show that the ice scours vary in width and depth. Trenches in the middle have a flat low inclined bottom. On the ortho-photo mosaic, it is seen that shrubs commonly mark side berms and rarely grow in the middle depressions, making deciphering easier. The features of the scours seen on satellite images at smaller scales are similar for smaller ice scours seen by detailed UAV investigations: curves and bends (polygon 1 and 2, Figure 12), presence of multiple parallel scours (all polygons, Figure 12) and overlaying of scours (polygons 1, 3, 4 and 5, Figure 12) are seen in the UAV images.

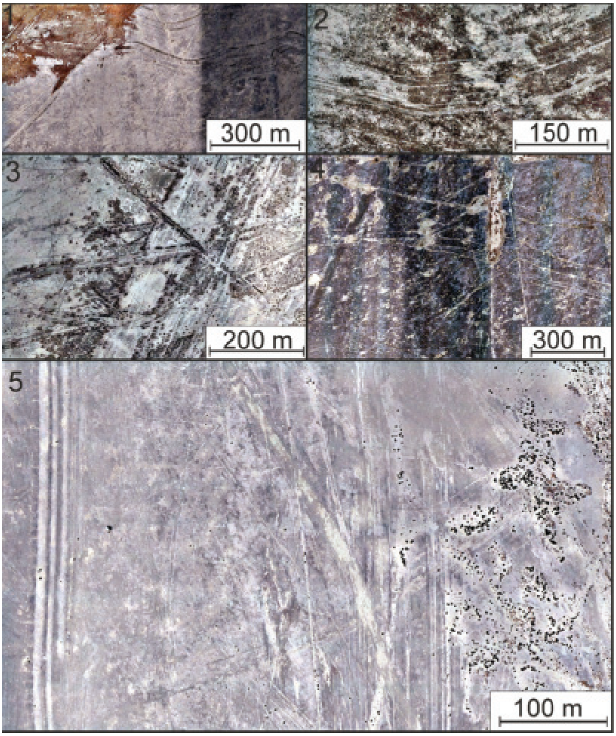


Figure 12. Results of the UAV survey in the northeast of the Aral Sea. The number in the left top corner corresponds to the number of the polygon in Figure 4

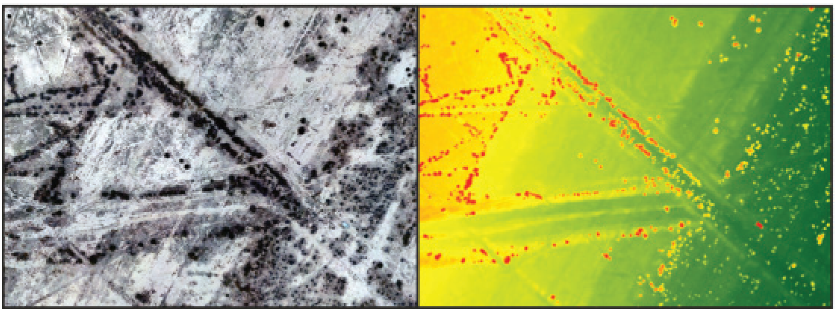


Figure 13. A fragment of the ortho-photo mosaic (left) and preliminary digital elevation model (DEM) (right) of polygon 3. Colors of the DEM show lower (green, 36 m a.s.l.) and higher (red, 37 m a.s.l.) elevations

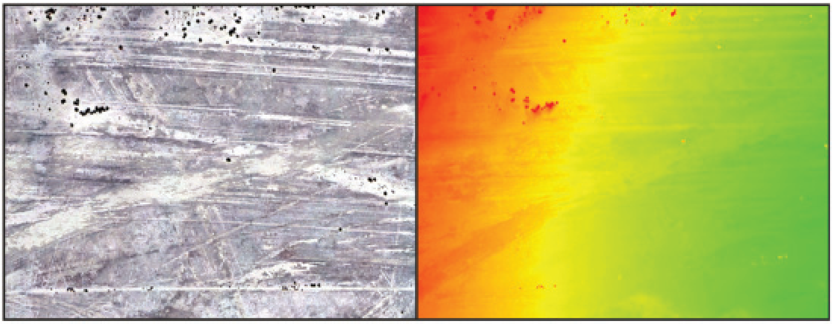


Figure 14. A fragment of the ortho-photo mosaic (left) and preliminary DEM (right) of the northern part of polygon 5. Colors of the DEM show lower (green, 34 m a.s.l.) and higher (red, 35 m a.s.l.) elevations

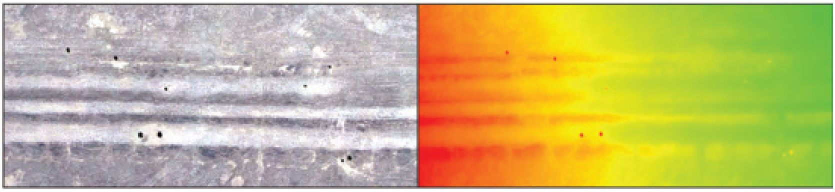


Figure 15. A fragment of the ortho-photo mosaic (left) and preliminary DEM (right) of the southern part of polygon 5. Colors of the DEM show lower (green, 34 m a.s.l.) and higher (red, 35 m a.s.l.) elevations

Distribution of the landforms on the former Aral sea bed

The conducted satellite imagery analysis implies that almost the whole former South Aral Sea is covered by the linear landforms which we identify as ice scours. The distribution of their coverage (Figure 16) shows that areas with the highest concentration of ice gouges (more than 50 % coverage) are situated in the central part of the East Aral Sea (to the east from the former Barsa-Kelmes Island, Figure 6) and in the southern part of the West Aral Sea, in the vicinity of the remaining reservoir. They occupy about 5 % of the whole Aral Sea region. Significant coverage (from 20 to 50 %) is typical for areas near the central part of East Aral, to the east of the former Vozrozhdeniya Island and Berg Strait; these areas occupy about 10 % of the whole region. The margins of the sea, as a rule, are less covered by the ice gouging landforms (0–20 %). At the bottom of the North Aral Sea, ice scours were totally absent.

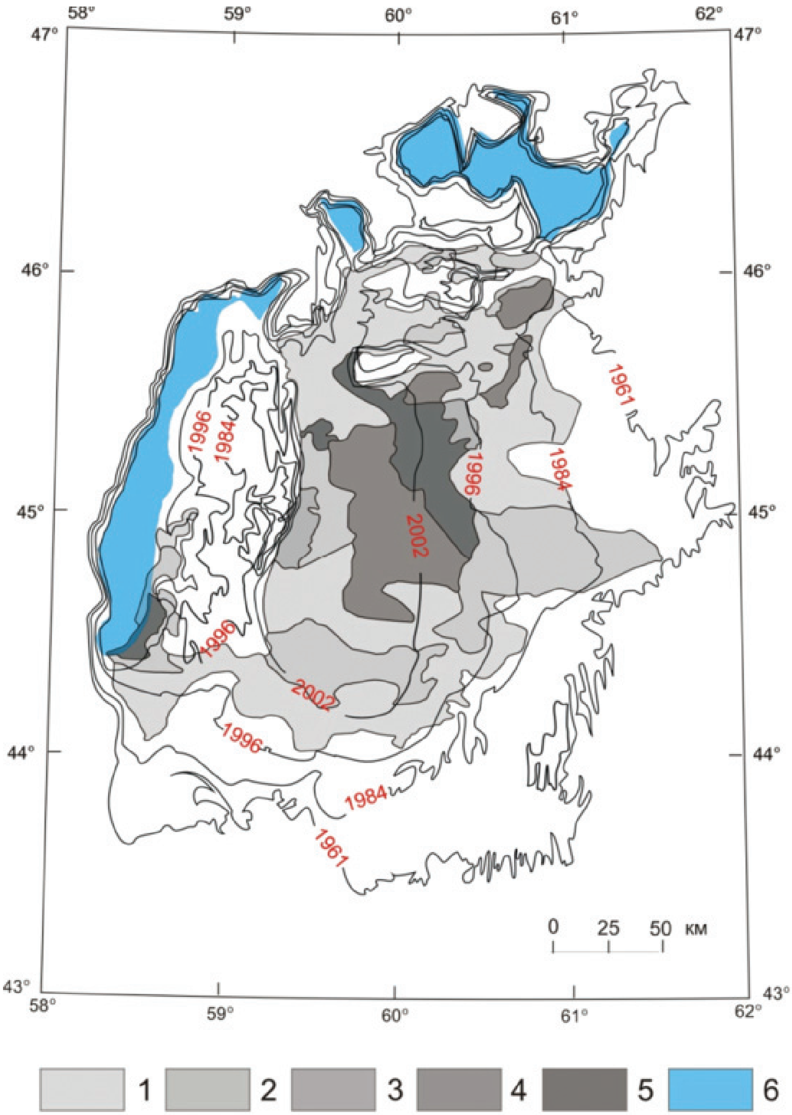


Figure 16. Estimated coverage of the Aral Sea bottom by ice scours: (1) < 10 % of ice scour coverage, (2) 10–20 %, (3) 20–30 %, (4) 30–50 %, (5) > 50 %, (6) modern Aral Sea water area. Background: contours of the former shorelines after [40]

DISCUSSION

Formation Mechanisms of the Aral Sea Ice-Gouging Topography

The morphology and distribution of the scours derived from satellite imagery and field analysis are in many ways similar to the ice-gouging topography of modern freezing seas and large lakes previously studied by side scan sonar (SSS) surveys [4,52] etc., allowing us to suppose their creation by ice. To prove the origin of the Aral Sea bottom landforms, we compared them to well-studied ice gouges in other seas and lakes. These included the Baydaratskaya Bay of the Kara Sea [53], because of its extensive coverage by SSS data during investigations for construction of an underwater pipeline crossing [4], the northern Caspian Sea [12, 19], which is less studied but is proximate to the Aral Sea and has similar conditions, and Lake Erie [23] because of its similar latitudes, water area and conditions.

Identically to ice gouges in these regions, all of the Aral Sea scours have specific morphology with a depression in the axis and parallel side berms, giving evidence of plowing of the bottom ground by ice formations. Relatively dense deposits in the depressions imply pressure of heavy sea ice formations, while looser sediments in the side berms suggest the effect of plowing of the bottom grounds. Both single scours and their combs can be encountered in all freezing seas and lakes ([3], Figure 17). Such combs appear when a grounded hummocky formation or stamukha plows the bottom with its multiple keels. These large ice formations are usually frozen into vast ice floes, increasing their weight and gouging force [54, 55]. The larger the ice hummock is, the more keels penetrate into the ground increasing the depth of the scours.

Another feature encountered in the Arctic Seas and in the Caspian and Aral Sea is that both the ice scours and their combs are often imposed (Figure 18) as a result of their consequent formation [3]. One single ice hummock can create numerous scours of different directions cutting each other, as it drifts along the winds and currents.

The scours and ice gouges in all freezing seas, including the former Aral Sea, have bends (Figure 19) which can be both sharp or smooth depending on the rates of the wind direction changes and on the topography of the coastal zone. Stamukha pits, appearing when a large ice hummocky formation (stamukha) is grounded on a shoal and is too heavy for the wind currents to move it, are typical ice gouging landforms as well.

A feature directly evidencing the ice gouging origin of a scour is the presence of front mounds both at the ends of the scours and along their sides (Figure 20). Such mounds, typical for ice gouges of the Caspian and Kara Seas were observed both in field (Figures 10 c,d and 12) and by remote sensing at the former Aral Sea bottom.

In addition, the distribution of the scours with their orientation correlating with the directions of the most frequent winds in winter [30], (Figure 8) makes it possible to reliably attribute the gouges of the Aral Sea to traces of ice impact on the bottom.

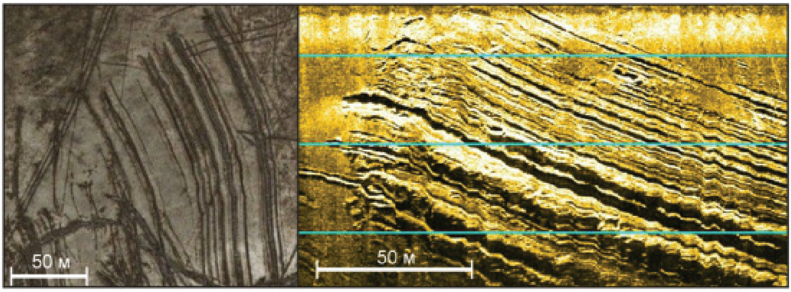


Figure 17. "Combs" of ice scours at the bottom of the Aral Sea (WorldView-3, left) [42] and at the bottom of the Baydaratskaya Bay (side scan sonar (SSS) survey, right)

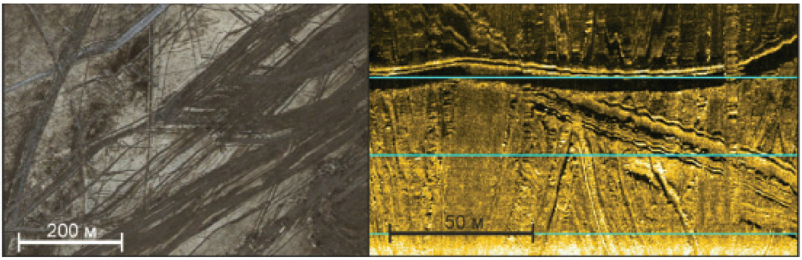


Figure 18. Imposition of ice gouging "combs" at the bottom of the Aral Sea (WorldView-3, left) [42] and at the bottom of the Baydaratskaya Bay (SSS survey, right)

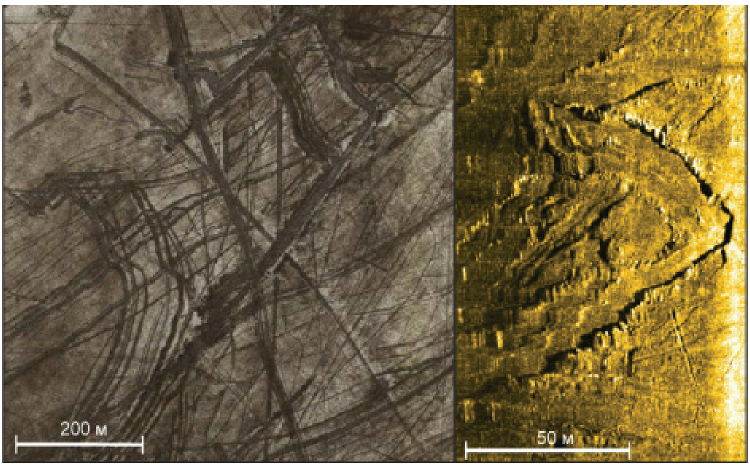


Figure 19. Bending ice scours at the bottom of the Aral Sea (WorldView-3, left) [42] and at the bottom of the Baydaratskaya Bay (SSS survey, right)

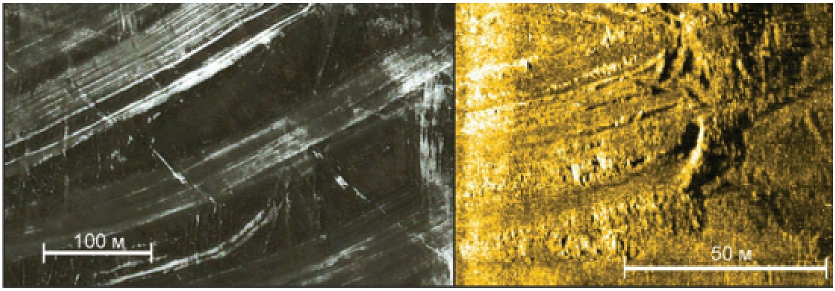


Figure 20. Front mounds at the ends of the "combs" at the bottom of the Aral Sea (WorldView-3, left) [42] and at the bottom of the Baydaratskaya Bay (SSS survey, right)

The morphometric parameters of the scours at the bottom the Aral Sea are also comparable to the dimensions of ice-gouging landforms in other modern freezing seas and lakes (Table 3). The ice gouges of Baydaratskaya Bay are presumably the longest; the SSS surveys showed them to be at least 2 km long; however, parallel surveying lines allow us to suppose much more considerable gouges of several kilometers or even tens of kilometers [4]. Values for the Caspian Sea, Lake Erie and the Aral Sea are comparable, making several kilometers. The Aral Sea ice gouges are wide in relation to other seas and lakes. They are also shallower than the ice gouges of the Caspian Sea, Kara Sea and Lake Erie. Firstly, all of the ice gouges at the Aral Sea were smoothened by waves during the water level decrease, while in all other seas, there are still deep water areas with little wave action and small sedimentation rates, where the scours remain well-preserved. Secondly, after the exposure, aeolian processes contributed to their further filling. Generally, the dimensions of the Aral Sea scours are of the same order as the ice gouging landforms of other freezing seas and lakes.

Table 3

Comparison of ice scours of the Aral, Caspian, and Kara Seas and Lake Erie

Sea	Average Length	Average Width, m	Average Depth of an Ice Scour, m	Average Water Depth of the Ice Scours' Formation, m	Preservation Time
Aral Sea	1300 m	15	0,2	2–5 (assumption)	decades
Caspian Sea [19, 29]	several km	5	1,0	2–5	few months
Kara Sea (Baydaratskaya Bay) [4]	several km	10	1,0	12–26	from 1–2 years to few decades
Lake Erie [23]	4,5–6,0 km	60–100	> 1,0	17–21	?

Ice-Gouging Intensity Patterns

As seen from Table 2, the average water depths at which the ice scours form vary greatly in different freezing seas and large lakes. On the one hand, the intensity of ice gouging depends on a large array of parameters, being the climate, mechanical properties of ice, bottom topography, etc. On the other hand, conditions of preservation of the scours can be different. As a result, the degree of ice impact does not correlate directly with the number of ice gouges seen on the bottom [3].

Areas close to the coast are usually occupied by fast ice, which moves little and does not form large hummocks; therefore, the forming gouges are small and shallow [1, 56]. They are usually destroyed by the first spring storm; therefore, the concentration of ice gouges in coastward regions is usually low. The area with the greatest intensity of ice gouging is the fast ice rim, along which the largest hummocks and ice floes usually drift [14, 53]. Deeper water areas are rarely affected, and can be plowed by the largest ice formations only, as their keels have to be very deep to reach the bottom. However, with no wave action and in the absence of currents, the ice scours can be preserved for many years, being repeatedly imposed. After a decade, this will result in high concentrations of gouges, while the ice impact on the bottom in fact occurs rarely.

In this way, the depths of the greatest ice impact vary in different seas, as the zone with the most intense ice action is attributed to the fast ice rim, not to a certain water depth. For Baydaratskaya Bay, Kara Sea, this zone lies at depths between 12 and 26 m [4]. The depths of ice gouging in the American Great Lakes (17–21 m, Table 3) are comparable to the Arctic Seas [23]. In the Caspian Sea, the zone of the most intense ice gouging was proved to appear in shallower water areas at depths of 2–5 m [29]. It has been previously supposed [23] that the depth of ice gouging is mainly controlled by accumulated freezing degree-days (AFDD). At Baydaratskaya Bay, the average air-freezing index calculated in the same way ranged from 3000 to 3500 [57], being the greatest. At the Caspian Sea this value was from 300 to 1300 AFDD [58], being greater than in the region of Lake Erie (285 to 582 AFDD, [23]). At the same time, the depth of ice impact at Lake Erie reaches 25 m [7, 23], while the maximum depth of stamukha penetration in the Caspian Sea is 12 m [11] with average values of 2–5 m [29]. The values for the Aral Sea at Barsakelmes Island in its middle part reach 316–1415 AFDD [59], being close to the Caspian Sea values.

The ice thickness does not correlate directly with the depths of impact either: it makes up to 1,2–1,4 m in Baydaratskaya Bay [60], while the average values for Lake Erie and the Caspian Sea are comparable: up to 0,5 m on the average, and never exceeding 0,8 m in Lake Erie [23] and not more than 0,6–0,7 m for drifting ice and 0,9–1,2 m for fast ice in the Northern Caspian Sea [11]. The modern ice thickness varies greatly in the West and the North Aral Sea and depends notably on local conditions; because of the salinity increase, ice thickness in the past should have been greater.

A factor controlling the depth of the greatest ice-gouging intensity might be the bottom topography and inclination of the underwater slopes. Lake Erie and Baydaratskaya Bay are characterized by steeper underwater slopes than the flat Caspian Sea bottom. The floating fast ice has a limited width; at some point it cracks and forms a fissure, along which its rim forms. If, e.g., Lake Erie has steeper underwater slopes than the Caspian Sea, the fast ice rim forming at the same distance from the coast in these two lakes will form at different water depth intervals. Therefore, areas with the most intense ice impact along the rim will be attributed to different depths. The Aral Sea had a very flat bottom in its central and eastern parts, comparable to the Caspian Sea. Therefore, the Northern Caspian Sea can be a model of the past conditions in the Aral Sea. Its extent is comparable to the past area of the Aral Sea; the Southern and Middle Caspian do not freeze and are much deeper, which makes ice gouging impossible. Northerly and northeasterly wind directions prevail in both regions. Moreover, the Caspian Sea and the Aral Sea are situated in similar continental arid desert climate, contrary to the Great American lakes, and experienced considerable water level fluctuations. In this way, we suppose that the patterns of ice impact in the past at the Aral Sea were comparable to the modern Northern Caspian Sea, with depths of the most intense ice gouging along the fast ice rim at 2–5 m. In the nearshore zone with 1–2 m depths, fast ice should have been stable and hummocking was not intensive. At depths of more than 6 m, hummocky formations were presumably not thick enough for their keels to penetrate into the ground.

The preservation of the ice scours at freezing seas is generally controlled by the wave base, which, in its turn, is influenced by the wind fetch, the size of the lake or sea and wind direction. Wave action could not be great at the Aral Sea. The winds blow from land both in winter and in summer and rarely affect the northeastern coast. As the wave base is close to the sea depth, the waves lose their energy, not reaching the nearshore zone. In the conditions of water level decrease, the depth of wave impact was controlled by the vast shallows, limiting sediment transport. This confirms the absence of scours to the northeast from the Vozrozhdeniya Island, and abundant scours to the southwest from it, in the wind shadow.

At the same time, unlike the Caspian Sea and at the Arctic seas, the distribution of ice scours at the Aral Sea bottom was influenced by another factor, absent elsewhere: its dramatic and rapid water level drop. While it could not affect the density of the ice scours, it promoted their unprecedented preservation. In one year, the coastline could retreat by several kilometers, and therefore the wave action did not have time to destroy the ice scours. The density of the scours, in turn, was more influenced by the local bottom topography and the width of the water surface affecting the acceleration of ice floes and the formation of hummocks. In this way, while the intensity of ice scouring can be compared to the Arctic seas and to the Caspian Sea, the coverage of the bottom by scours is in some way a snapshot showing both old ice scours with good preservation and young scours which formed in one winter that would otherwise have been destroyed by waves.

This unique snapshot setting raises the interest in complementary simultaneous studies of the Northern Caspian and Aral Seas. Because of their comparable climate, the mechanisms and patterns of sea ice effect should have been similar in the past.

Today, the Northern Caspian still represents conditions typical for the Aral Sea several decades ago. Its ice gouging landforms are seen on the remotely sensed images only immediately after the water area becomes clear of ice (Figure 21). Then, they are eroded by the first spring storms. As the studies of parameters and distribution of such forms are constrained by their short lifetime, good preservation of ice gouges at the silty Aral Sea bottom ground after the level drop allows us to investigate similar landforms and extend the results to the Northern Caspian.

At the same time, while today conditions in the Aral Sea are not favorable for ice gouging, there is a possibility to reconstruct such past conditions by observing modern sea ice and analyzing different ice phenomena in the Caspian Sea (Figure 22). Similarly to the modern Northern Caspian, in the Aral Sea, multiple ice floes collided under the wind force, forming ice ridges that could affect the bottom.

Figure 21. Ice scours on the Northern Caspian Sea bottom, Tyuleniy Archipelago (acquired 16 April 2016) [61]

Stamukhas were breaking off the ice cover and contributing to the new hummocking. In this way, the Caspian Sea provides an opportunity for investigations of ice conditions, mechanisms and processes of ice gouging, while at the Aral Sea, the results of such processes can be documented. Further comprehensive studies of the two seas could add to our understanding of the ice-gouging processes in the mid-latitude climates.

In this way, the distribution of the scours in the Aral Sea and their density patterns (Figure 16) are a result of both the varying ice-gouging intensity and the different degree of their preservation. The spatially non-uniform intensity of ice impact resulted in lower concentrations of ice scours in the coastward parts, while in the central part, there were more ice gouges, just as in Baydaratskaya Bay [4] and the

Caspian Sea [63]. The largest coverage of the central part of the Eastern Aral Sea by scours was also provided by their long-term accumulation when the water level was at 2–5 m above vast flat bottom plains in its center. Moreover, a fast water level drop promoted the preservation of bottom fragments with high ice scour concentrations even in relatively shallow areas. Despite the northerly and northeasterly winds, which pushed the ice to the south in the Caspian and Aral Sea, most of the Aral Sea ice gouges are concentrated in its flat central part. On the one hand, the southern coasts were protected by the fast ice. On the other hand, the coastline retreated faster in the north and east, while in the south, water remained until the 2000s. Therefore, old ice gouges from the 1990s remained in the central and eastern part, and were destroyed by waves in the south. Younger ice gouges from the 2000s were less abundant as the air and water temperatures increased, along with the salinity; the ice formations became smaller and could execute less impact on the bottom. At the North Aral Sea, the small size of the water area, insufficient to speed up drifting ice and hummocks, and its complete freezing every year limited ice gouging. The West Aral Sea could not provide favorable conditions for ice gouging because of its high salinity and steep nearshore bottom slopes. Therefore, there are no ice gouges neither at the North Aral Sea nor near the western coast of the West Aral Sea.

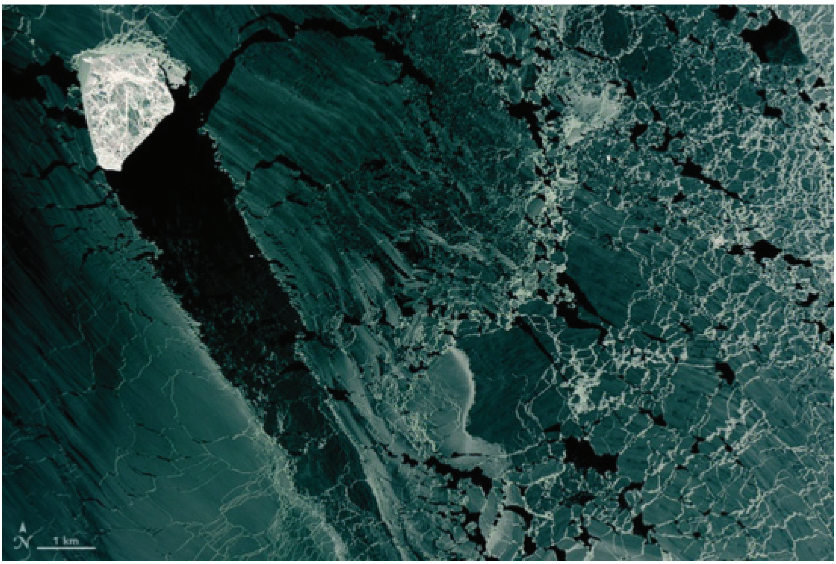


Figure 22. Ice conditions at the Northern Caspian Sea on 4 February 2017 [62].
Ice hummock (stamukha) grounded on the seabed and open water trace behind it

Temporal Evolution of the Aral Sea Ice-Gouging Topography

Knowing the position of the retracting Aral Sea shoreline in space and time [40] (Figure 16), and assuming that the most intense ice impact is typical for depths of 2–5 m, similarly to the Northern Caspian, we were able to reconstruct the history of the ice-gouging topography at the Aral Sea bottom. Based on the known rates of lake level fluctuation, the formation time of separate scours can be estimated. We suggest that most of them formed along with the rapid sea-level fall of 1980–mid-1990s when the depth interval of 2–5 m at the East Aral generally shifted westwards along with the coastline. During this whole level fall, the zone of intense ice impact moved from depths of about 15–18 m to 22–25 m in relation to the 53 m base elevation. The rate of water level drop (reaching 70 cm per year from the mid-1970s to the early 1990s) was so high that the ice scours could not be filled with the bottom sediments. In one year, several kilometers of the former bottom surface became exposed, providing an unprecedented degree of ice-gouging topography preservation. In the mid-1990s and 2000s, the shallowing slowed down, and extensive shoals formed. At that time, vast areas were in conditions favorable for ice gouging (2–5 m depths). At the same time, the wave action on the east coast was almost absent due to its flat topography, small depths and prevalence of storm winds blowing from the northeast. In the late 2000s, the waters of the East Aral Sea became hypersaline, and the ice formation diminished. The surface area of the sea reduced to such an extent that rare ice could not get enough acceleration for the hummocking. The ice-gouging processes, therefore, largely ceased.

Today, ice gouging is almost absent at the Aral Sea. The East Aral Sea, which used to be the area with the most intense ice impact, has now entirely dried out. In the West Aral Sea, the water is hypersaline, and ice forms at extremely low temperatures; it is thin and incapable of plowing the bottom. On the North Aral Sea, ice gouging is limited, as it always was. Today, no significant regional climate or anthropogenic drivers can cause an increase of the Aral Sea level [64], so it is unlikely that the ice effect on the bottom will intensify in the nearest future.

CONCLUSIONS

At the bottom of the former Aral Sea, exposed after a dramatic man-induced fall in waterlevel, linear landforms were recently discovered [28,63]. Their analysis using remote-sensing and field (UAV and geomorphological) methods has shown that the landforms range from 3 to 90 m width (15 m on the average), from 100 m to several km length (1 km on the average) and have a depth of up to 0,5 m. Areas with their greatest density are situated in the central part of the former East Aral Sea. The forms were proved to be ice gouges and scours made by drifting ice during higher water level position in the past. We have shown that the climate of the Aral Sea region provided favorable conditions for ice scouring of the bottom by hummocks both before and during the water level fall. The directions of the scours correspond to the most frequent winds in the cold season. Their morphology, morphometry and distribution are typical for ice scours, known in the Arctic, Caspian and other freezing seas and large lakes. Just as with the ice scours of the Caspian Sea, Kara Sea and other freezing seas, the gouges of the Aral Sea have a trench in the middle surrounded by ridges; they make both sharp and smooth bends and curves; they are often juxtaposed; front mounds are documented at their ends. The evolution of the ice impact on the Aral Sea bottom was determined by changes of the lake level since the 1960s. The most intense ice gouging happened in the 1980s–mid-1990s, when the zone of the greatest impact (2–5 m depths) shifted from 15–18 to 22–25 m a.s.l. In the 1990s–2000s, the shallowing slowed down, and ice scours continued to form at extensive shoals. In the late 2000s, ice gouging ceased as a result of salinity increase and water area decrease; it is unlikely to intensify in the near future. The Aral Sea represents a unique setting for studies of ice-gouging topography. No other present or former water body provides such vast areas of exposed bottom with scours that are relatively easy to access. Due to a very rapid water level fall, good preservation of ice scours became possible. On the exposed bottom of the Aral Sea, we can see a snapshot of gouges that formed during a single season and areas with the results of repeated impact.

Author Contributions: S.M. Aral Sea geomorphology field data, remote-sensing data interpretation, paper writing and preparation; S.O. project administration, conceptualization, supervision, funding acquisition, review and editing; A.B. conceptualization, review and editing, paper writing (Discussion and Conclusions); A.V. photogrammetric field data and its processing, visualization; V.A. Baydaratskaya Bay field data; P.B. Caspian Sea field data.

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MARINE OPERATIONS IN CHANNELS THROUGH SHALLOW ICE-COVERED WATERS[15]

ABSTRACT

Current trends show decreasing water level in the Caspian Sea. This is a doomsday scenario for marine operations in the Northern part of the sea. Shallowing waters may limit both access to the sea through Volga-Caspian Channel from the world as well asinternal cargo transit operations to big existing projects at Kashagan and Prorva areas and several smaller projects scattered in the Kazakh sector of the Northern Caspian. Ongoing dredging initiative along the Volga-Caspian and Prorva Channels is targeted to cope with intensive backfill due to significant sediment transfer. This paper is targeted to address ice related hazards to marine operations in these shallowing conditions during winters. Ice drift across the channels pushing vessels off channel and grounding in surrounding shallower waters is the major scenario of interest to assess in order to forecast event during operations and issue timely alert to operators.

KEYWORDS: Operations in Ice; Grounding Vessels; Ice Drift; Remote Sensing; Wind and Drift Forecast.

INTRODUCTION

The North Caspian Sea is an area of continuously growing marine operations mainly supporting oil and gas activities. Existing projects on the Kazakhstan side include the oil producing field, Kashagan and the transport of modules to Prorva on the eastern coast. Several smaller projects are expected to go operational in the next 10 years or so. These include Pearls, offshore Kalamkas, Zhanbay as well as the next phase of Kashagan development. All these are likely to continue using marine support with the existing fleet that has access to the North-Eastern part of the sea through the Saddle, a shallower area that sets a constraint on vessel draft. Major projects in the Volga delta area include the Korchagin and Filanovsky oil fields in the deeper waters of the Russian sector and the Volga Caspian channel.

The latter project supports Russian oil and gas offshore developments and opens the marine trade route between Caspian states and world markets by providing access to the sea through the network of Russian rivers. These major projects in the Volga delta complete the full picture of anthropogenic activities in the shallow northern Caspian.

[15] Marine Operations in Channels through Shallow Ice-Covered Waters / P. Buharitsin, Anton Sigitov, Sergey Vernyayev, Yevgeniy Kadranov, Andrey Bukharitsin // Материалы of the 25th International Conference on Port and Ocean Engineering under Frctic Conditions POAC,2019. Delft, the Netherlands, june 09–13, 2019. (электронный вариант, на флэш-карте). – С. 1-15.

The latest studies agree that the most likely scenario is for water level to continue its decreasing trend. This will make already challenging operations in shallow waters even more complex. Figure 1 illustrates water depth at the Saddle and Kashagan East, the two most vulnerable regions with ongoing operations.

The plot is based on the historical records of annual average water level until 2017 (derived from Coordination Committee on Hydrometeorology of the Caspian Sea (CCH), 2019) and projected until 2025 with rate of change suggested by Chen et al (2017). The major focus of this study is an analysis of the effect on marine operations in ice for a 3 m draft vessel for five categories of accessibility (Red is unpassable. Blue indicates no effect from water depth) and shown in the same figure. A draft of 3 m is typical for the shallow draft ice breaking supply vessels that form the majority of the north Caspian fleet.

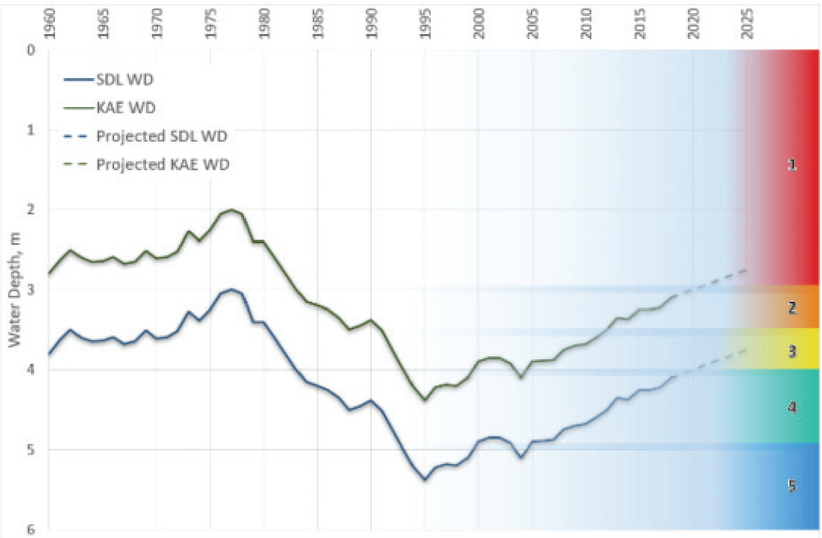

Figure 1. Water Depth at Saddle (SDL) and Kashagan East (KAE) based on annual water level variations in the Caspian Sea derived from CCH, 2019. Accessibility index for a 3 m draft vessel: Red (1) – Inaccessible; Orange (2) – Slow cruise speed with intermittent grounding to seabed; Yellow (3) – Slow cruise speed with high risk of grounding; Green (4) – Normal operations in shallow waters (restricted cruise speed); Blue (5) – no restriction

Figure 2 below illustrates the effect of changing water depth on accessibility to different areas of the Northern Caspian by vessels with a draft of 3 m. The maps illustrate accessibility, using the same colour cade as Figure 1, for annual average water levels ranging from +1,0 m Caspian Datum (–28 m Baltic Datum) to –1,0 m CD. The analysis excludes the effect of both negative and positive water surges due to strong wind events. Accessibility classification is based on distribution of projected water depths. The present-day situation is close to that illustrated for the –0,5 m CD water level.

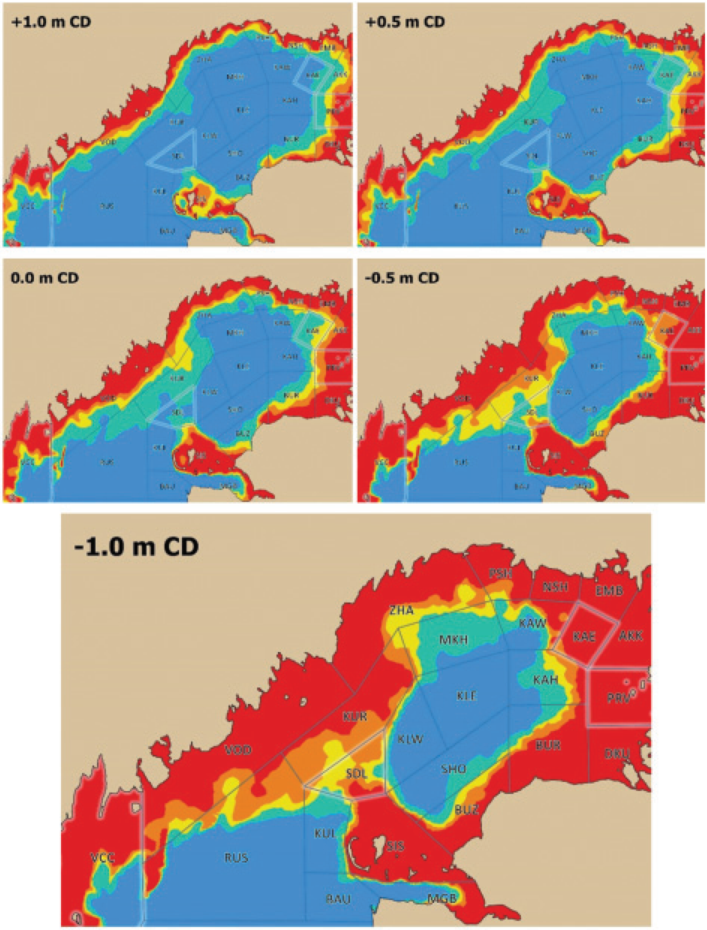

Figure 2. Accessibility analysis for marine operations in the Northern Caspian for vessels with 3 m draft: Blue – no restriction; Green – Normal operations in shallow waters (restricted cruise speed); Yellow – Slow cruise speed with high risk of grounding; Orange – Slow cruise speed with intermittent grounding to seabed; Red – Inaccessible. Crucial areas for operations in the Northern Caspian (VCC – Volga-Caspian Channel, SDL – Saddle, KAE – Kashagan East, PRV – Prorva) are highlighted

Considering the decreasing water level trend and accessibility analysis above, where -1,0 m CD is possible in the next 10 years, operators in the Eastern part of the Northern Caspian might consider dredging the Saddle (SDL) and the approaches to offshore blocks to ensure continuous access to existing offshore production and exploration facilities. This will allow marine fleet operations to continue to supply existing infrastructure. An alternative means of transportation such as air cushion vehicles could also be used. Both alternatives require significant effort in maintenance and continuous analysis of windows of opportunity for operations to take place.

The initiative to build and maintain navigation channels requires continuous dredging due to intensive silting as observed in the Volga Caspian channel. Rigorous Ice Hazards Management systems are also required to avoid impact on marine operations in ice, as discussed in this study. ACVs require significant path finding effort to ensure the smallest ice surface roughness along the route in order to reduce maintenance costs on damaged skirts. ACVs also require quality regional weather monitoring for unfavourable conditions that may lead to ice accretion.

The goal of this particular study is to assess the operability of dredged channels during winters considering ice related hazards associated with drift. Two major scenarios were mentioned in the history of operations along the Volga-Caspian channel:

1) Ice drift across the channel leading to vessels grounding outside the navigable part of the channel;

2) Ridging across channels, stamukhi and large grounded rubble fields formation as shown in Figure 3.

Figure 3. Illustration of ridged grounded features forming in vicinity of Volga-Caspian channel. (Bukharitsin, 2011)

While ridging can be a limiting factor, it can be managed with ice clearing missions within navigable areas, though these are time consuming. This may temporarily disrupt the logistical chain, but the impact is not as dramatic as a vessel being pushed out of the channel into unnavigable areas. This would disable for the season while grounded a vessel in the shallows, with a high potential of damage from recurring drift events. Hence, the major focus of this paper is on ice drift events and their consequences.

The following tasks were performed in the scope of the assessment:

1) Investigation of historical records of operations in the Volga-Caspian channel from the Soviet era to the present. These case studies define weather parameters influencing hazardous ice and metocean conditions that resulted in significant impact on operations.

2) Assessment of the likelihood of events occurring based on historical weather records in the areas with high potential to be dredged for channels in future.

Results of this study may facilitate continued safe marine operations in ice with minimum disruption in the supply chain using advanced ice and metocean hazard monitoring systems.

MARINE OPERATIONS AT VOLGACASPIAN CHANNEL

There are several existing records of vessels receiving damages ranging from bent plates to damaged rudders and propellers. As reported by Hydrometeoizdat 1992 there are records of destroyed navigation signs along the channel (1938–1939, 1944–1945, 1948–1949). Removing navigation signs and stopping navigation for winter resulted in financial impact. Majority of incidents in the channel were caused with drift associated with crosswinds. This way MV "Krasnyi Kaspiy" and "Pobeda" were pushed off the channel in December 1950.

Volga-Caspian Channel has the longest operational history on the record with marine operations taking place continuously for a long time with increasing intensity since 1940s. Figure 4 shows position of the channel in the Western part of the Volga Delta.

The most dramatic case of ice drift affecting marine operations occurred in 1981 and was observed in the Volga-Caspian Channel. MV Baku was pushed off the channel and grounded in the shallow waters next to it. Figure 5 shows the timeline of events before and after the incident with the vessel as well wind records extracted from ERA5 reanalysis dataset. Figure 6 shows ice charts compiled during the two overflights before and after the grounding incident that indicate extensive new ice formation in front of Volga Delta that ensured continuous supply of ice to be drifted across the channel. Intensive westerly drift across the channel during the period from February 14th to February 18th was associated Eastern wind ranging between 25 and 30 knots gusting up to 40 knots as reconstructed from ERA5 dataset by The European Centre for Medium-Range Weather Forecasts (ECMWF) and correlating with observations by Astrakhan Ice Service, 1981. The drift event persisted with milder North-Eastern winds for several days afterwards that drifted large floes of grey ice towards the western coast from the central part of Volga Delta.

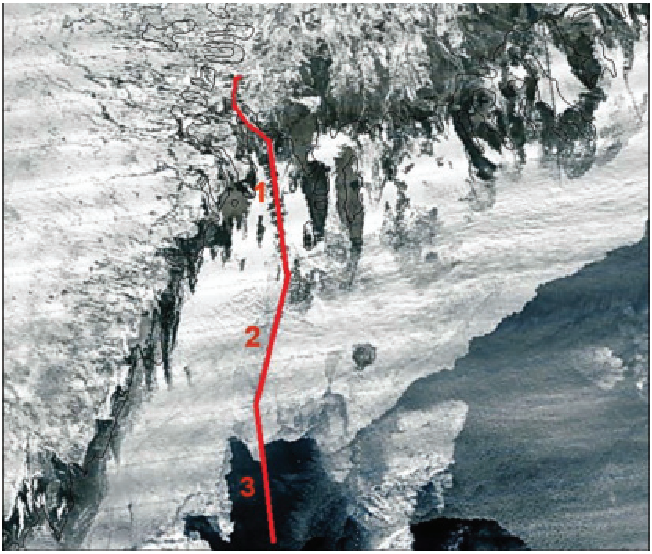

Figure 4. Orientation of Volga-Caspian Channel
(1 – River part of the channel; 2, 3 – Sea part of the channel)

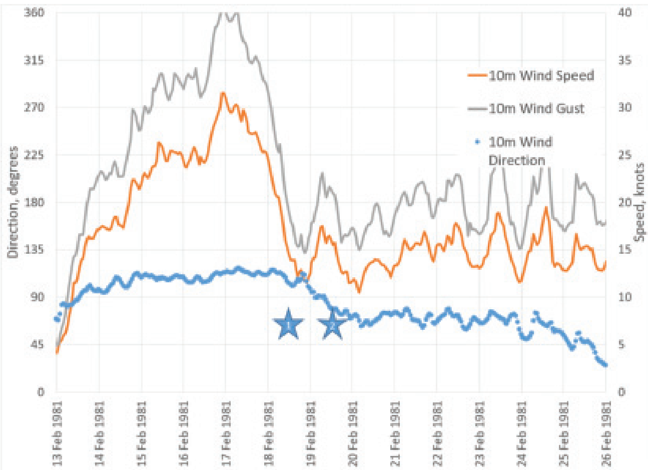

Figure 5. Wind Direction, Speed and Gust before and after grounding event with Baku (1) generated using Copernicus Atmosphere Monitoring Service information, 2019.
2 – Aerial Ice survey along the channel confirming ice conditions and capturing consequences of the incident with MV Baku

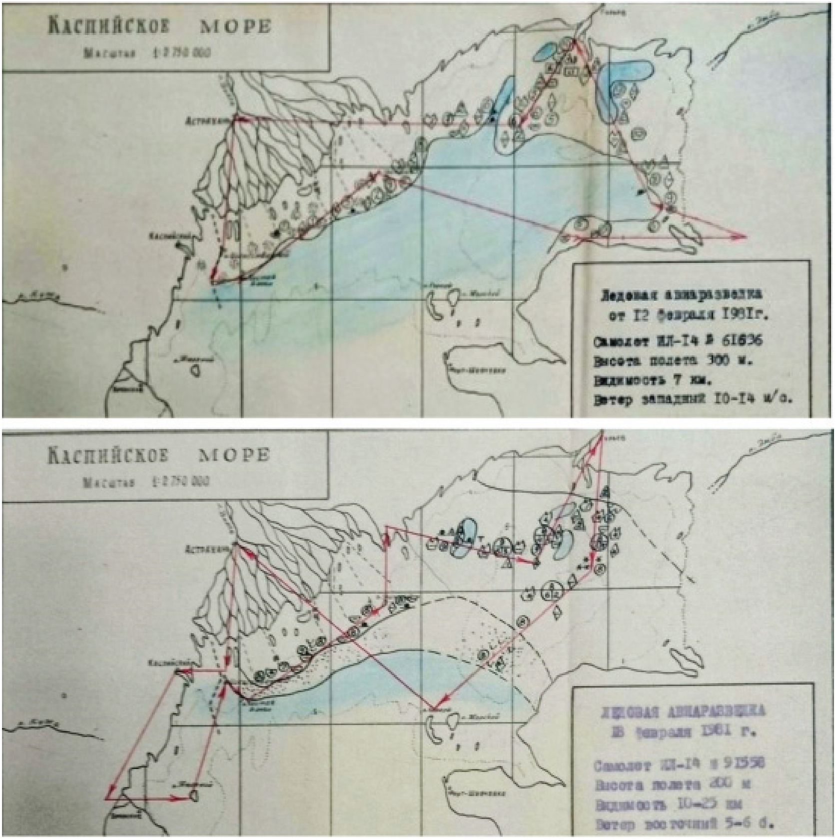

Figure 6. Aerial Ice Reconnaissance charts confirming ice conditions conducted on 12th and 18th of February 1981. Astrakhan Ice Service, 1927–1997

The bulk carrier MV Baku was in shore bound Icebreaker supported convoy through the marine part of the Volga Caspian Channel, when it was pushed off the channel with westerly drift on February 18th, 1981 that was. The vessel kept drifting with ice for the next two days while the upsurge caused by the Easterlies allowed her advancing through the shallows. Aerial survey has confirmed position, where she stopped drifting when grounded to seabed 10 km away from the channel (see Figure 7). Water level recovering to its normal state after upsurge flooding the area along the western coast made the grounding even more intensive. While Ice Breakers servicing the channel were not able to assist the rescue operation due to draft prohibiting to operate outside the channel only Shallow Draft Tug could provide assistance. As the tug did not have enough power to unground the vessel it stayed there until the next upsurge event later in the season.

Figure 7. Bulk Carrier MV Baku on seabed and SDT attempting to unground the vessel.
Photo by Bukharitsin P.I. 1981

DRIFT EVENTS SCENARIOS

Case studies from the Volga-Caspian Channel allowed identifying three scenarios to be considered in the project with major wind parameters and ice conditions that can lead to occurrence of hazardous ice drift events across channels:

#1: Assuming East West orientation of potential channel at Saddle Southerly and Northerly winds are likely to cause drift across the channel. Being close to Ice Edge with highly mobile ice cover in the area it is very responsive to wind. However, 2-days persistence is set to ensure cases leading to significant drift events is chosen;

#2: This scenario is targeted to define frequency of downsurge events that may cause significantly higher speeds of drift across channel and, thus, higher loads on vessels in channel with recovering water level afterwards (Figure 8).

#3: this scenario is targeted to define frequency of wind events that may cause cross drift in the channel. Considering they have led to significant consequences such as case with MV Baku discussed above they are of major interest to operations. For the same reason it is used for verification to existing records of drift derived from satellite imagery versus wind records for the area.

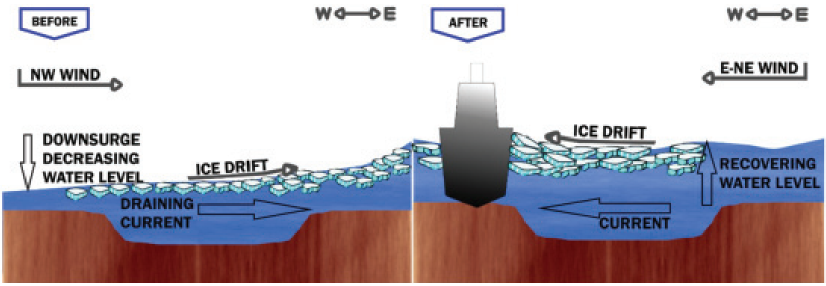

Figure 8: Schematic view of coinciding environmental phenomena described in VCC#2 scenario (VCC#2)

Wind parameters that are used in further analysis are summarised in Table 1 below.

Table 1

Wind parameters used to assess possibility of ice drift across existing Volga-Caspian channel and projected channel through Saddle

Scenario	#1	#2	#3
Area	Saddle (SDL)	Volga Caspian Channel (VCC)	Volga Caspian Channel (VCC)
10m Wind speed, knots	Above 15	Above 20	Above 15
10 m Wind Direction, degrees	300–60, 120–240	270–360	30–150, 210–330
Wind persistence, days	2	2	2
Scenario Description	Crosswind at channel	Downsurge leading to currents across channel with recovering water level	Crosswind at channel

ANALYSIS OF WIND AND DRIFT EVENTS OCCURRENCE

ERA5 atmospheric reanalysis of the global climate by ECMWF was used to extract records of wind at 10 m. This reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics spanning back several decades. Being publicly available at sufficient spatial resolution and relatively reliable records this dataset was chosen to perform the study. Historical records starting from 1979 were used to perform persistence analysis following conditions laid out for the three scenarios discussed above during periods starting in the beginning of November and finishing end of March each season. Presence of ice during the date ranges with weather conditions that are likely to cause drift was confirmed with visual observation of ice cover using remote sensing data (MODIS) since 2000, aerial ice reconnaissance charts from 1979 to 1991 and NOAA between 1991 and 2000 with low reliability due to extremely low resolution.

Figure 9 illustrates results of persistence analysis where frequency of identified events occurrence satisfying criteria laid out above is distributed by month of a season and season when they were observed regardless of ice presence. Each sector in a record indicates one event, absence of circle indicates no events answering scenario were identified. Fully coloured circle indicates there were four events observed at that month of corresponding season. There is only one such record (March 1995–1995 VCC#3) in the pivot chart that has 5 events. Season duration was set to start on November 01st and finish on March 31st. It should be noted here that occurrence of the events is uneven from season to season. So, for Saddle (SDL#1) and downsurge at VCC (VCC#2) scenarios that have boundary conditions of rare events, as example, there were seasons when events occurred rarely or didn't happen at all for two or three seasons in a row.

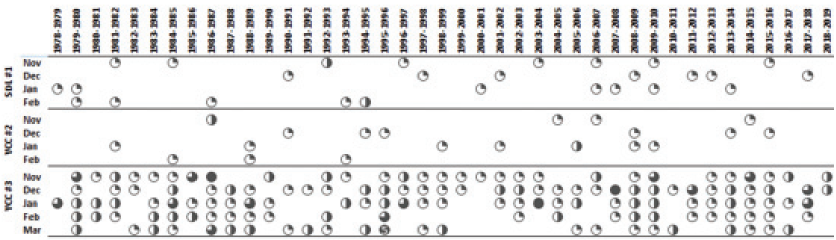

Figure 9. Frequency of occurrence for events answering conditions of scenarios distributed by winter months and seasons when they were observed.
Each quarter of a circle is one event that falls into a month of a season

Scenario 1 – SDL Crosswind

Persistence analysis has shown that there were 29 events during the last 40 years that might lead to cross drift events at Saddle. This confirms dominating winds in the region coincide with assumed channel orientation and unlikely or very rare events of persisting winds in Northern or Southern sectors. Figure 10 (top left) shows their distribution of occurrence by month of a season indicating even distribution through the season. The same figure indicates the same events when cross wind events coincided with significant ice confirmed present over the area totaling overall 18 events.

Depending on winter severity ice was present only once out of nine observed events in November and four events out of seven in December. Ice was present for all events in January and February and there were no such conditions in the history of the last 40 years that could cause crosswind drift in March.

Scenario 2 – VCC Downsurge

This is the other rare event scenario that has identified only 22 events in the history. 15 cases coincided with ice presence (Figure 10 top right). Ice presence coinciding with weather parameters that could cause the event was observed only once in November and there were no such conditions observed in March at all. There was no ice observed when event could happen for at least one case for December January and February.

Scenario 3 – VCC Crosswind

This scenario contained the most common conditions that were observed in the region. There were 225 cases that have answered persistence analysis criteria for crosswind conditions in the Volga Caspian Channel area. 137 events observed during the last 40 years including the one with MV Baku coincided with ice presence. Generally lighter ice conditions in the western part of the Northern Caspian resulted in only 8 cases out of 47 and around half of cases in December and March to take place with ice presence in November.

WIND TO DRIFT ANALYSIS

Ice drift records for Volga Caspian channel area during the period from 2010 to 2018 were extracted from ICEMAN.KZ database (Kadranov et al, 2017). Comparison algorithm of drift to corresponding wind observations from ERA5 reanalysis by ECMWF is described in detail by the same authors. Figure 11 shows timeseries of wind and drift directions and speeds records for several cases in 2012 and illustrates cases when directions of drift and wind closely match or have deviations from each other either due to effect of proximity to obstacles (Coast, seabed configuration, stamukhi) or flaws in data acquisition program. The flaws are normally associated with longer periods between start and end of drift displacements used to derive drift versus more frequent wind observations as can be seen with the right most record in the figure.

Comparison of all the records has shown almost no deviation of persistent drift direction from corresponding wind direction except for rare cases for wind blowing to sector from South to West as shown with scatter plot in Figure 12. The match confirms that majority of drift events have wind drag origin and have little effect from other forces as it is observed in the Arctic pack ice, where 30° deviation of drift from wind is normal, for example. Thus, historical persistence analysis of scenarios containing wind direction and speed as boundary conditions as discussed in the sections above is very close to what can be expected in the resulting drift.

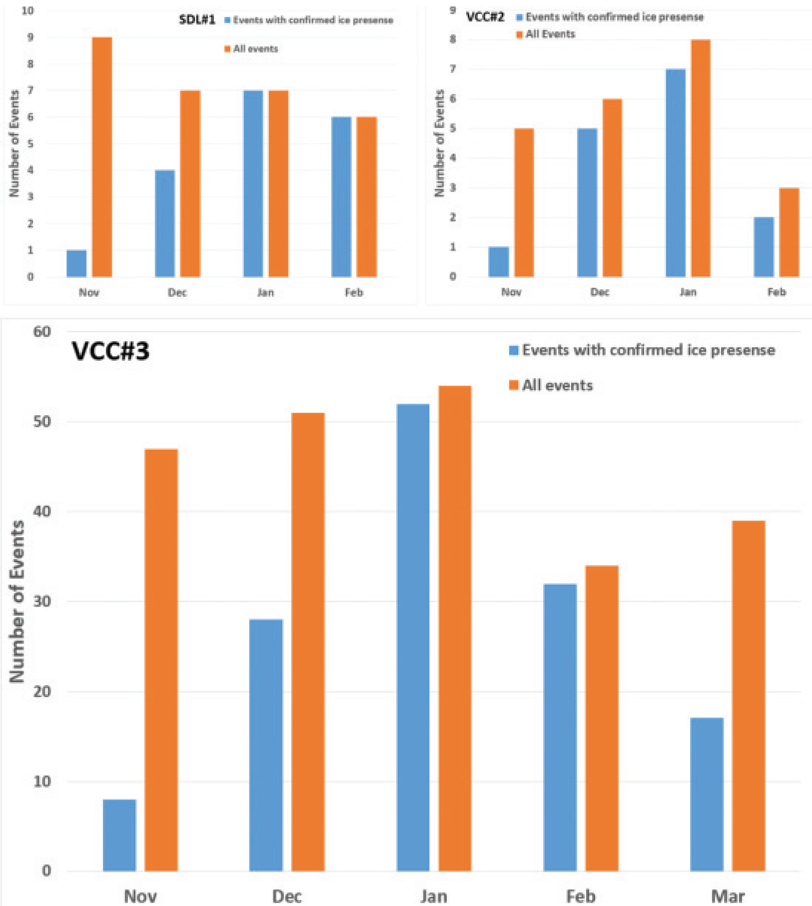

Figure 10. Number of events per month and number of events with confirmed presence of significant ice in the area as observed at Saddle during the period from 1979 to 2019 for Saddle (SDL) Case#1 – Top Left; Volga Caspian Channel (VCC) Case #2 – Top Right; Volga Caspian Channel (VCC) Case #3 – Bottom

Ice drift and Wind speed by distributions are illustrated in Figure 13. These distributions indicate the effect of proximity to coast with generally lower drift speed records in westerly directions although significant number of wind records indicate wind was blowing that way. It should be noted that there is low number of Northerly drift records in the area showing the direction is unfavourable due to configuration of the coastline reducing likelihood of ice drifting up the channel. Considering the correlation of wind and drift directions discussed above it should be noted that wind rose indicates the strongest winds correspond to the fastest drift speeds observed in ESE sector. Greater speeds in this direction can also be explained with unconstrained drift seawards in that direction.

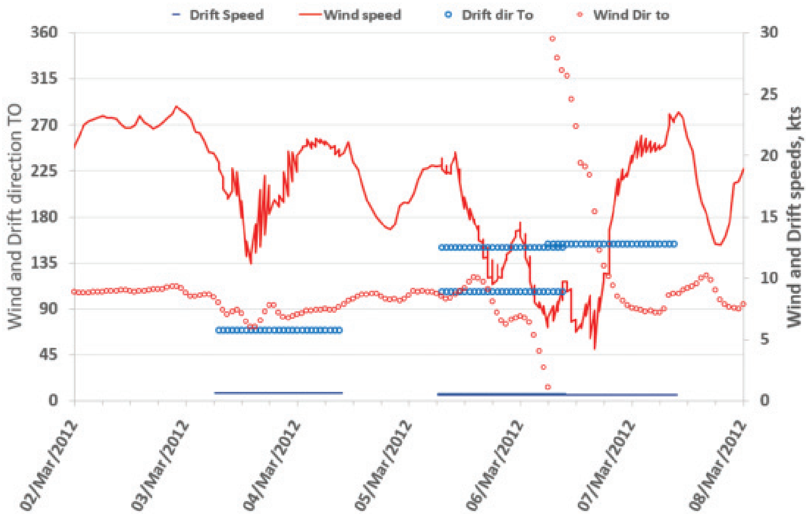

Figure 11. Example of Wind and Drift Direction
and speed timeseries for some of the records in 2012

DISCUSSION

The study of weather records during the last 40 years shows that unfavourable conditions for vessels crossing an E-W oriented channel through Saddle are rare (only 29 events in the history) and may not occur for three seasons in a row. The other scenario when drift is caused by combined action of wind drag and currents associated with recovering water level after downsurge is a rare occasion too. Although there were only 22 such events observed in the history for the given period cumulative effect of both driving forces causing drift may lead to higher impact on marine operations and should not be neglected.

As for more critical cross wind scenario in the Volga Caspian Channel that runs across predominant directions of wind observed in the region it is a normal occasion. It should be expected at least once each month of a season that ice drift poses risk to push a transiting vessel off the navigable part of the channel as it happened with Baku.

Analysis of drift data derived from satellite imagery over Volga Caspian Channel confirmed the most critical drift events involving highest ice displacements across the channel were wind driven with little effect from other factors. Although some caution is needed to interpret wind persistence analysis for areas where proximity to anchoring points and coastline has significant effects on drift.

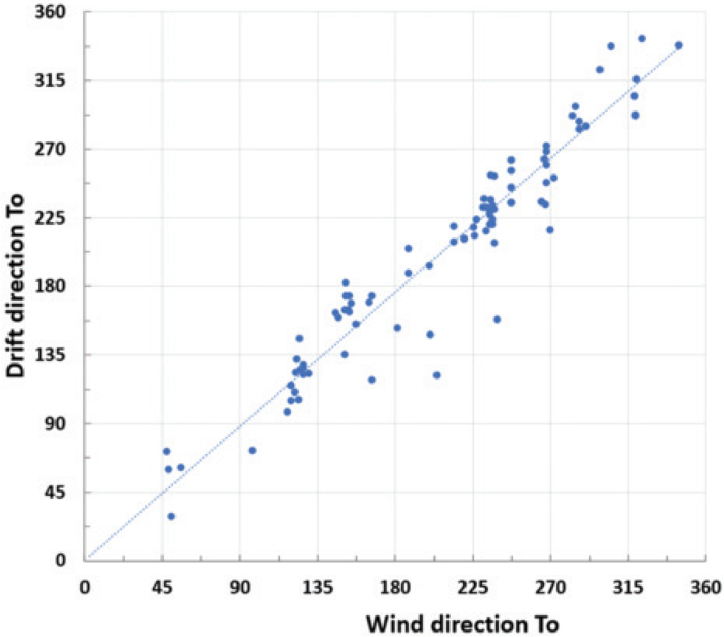

Figure 12. Distribution of ice drift direction
by wind direction for corresponding observations in the area

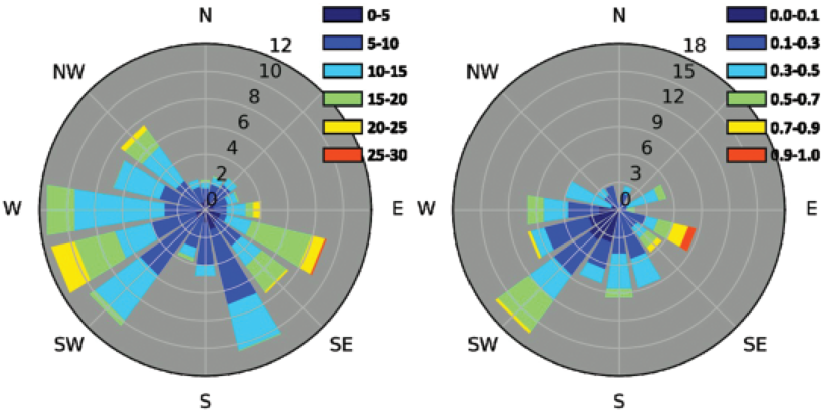

Figure 13. Wind speed (left) and Drift speed (right) distribution by direction TO (both for drift and wind) for observed drift events in vicinity of Volga Caspian Channel

In order to perform economic feasibility study of dredging activities and following channel operations, this analysis can be enhanced to take into consideration wind surge events that affect water level over shallower Eastern part of the Caspian, where dominating Easterlies keep water at generally lower levels than average that is considered in this study. Adding records on spatial distribution of mobile and stable zones as well as records of drift speed estimated over vast areas may clear uncertainties with drift occurrence due to wind events and help to estimate cumulative downtime expectations.

At the first glance, as authors see the results of this study, the risks of operating channels in shallow Caspian waters will require rigorous ice hazards management program to monitor current and forecast near future ice and weather conditions and to keep operations aware of expected hazards to make decisions on transits. Expanding the analysis into older historical records when water level was at critically low levels in the end of 70s and subdividing records by proximity to ice edge and major indicators characterising winters in the region such as Freezing Degree Days (FDD) and Thickness distribution, Ice Coverage and Volume, Mobility will increase forecasting accuracy of the events occurrence during future operations and, thus, improve overall safety of operations as well as decrease downtime of fleet in transit saving costs and increasing efficiency.

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- aviation and space observations of the ice cover in the river and sea, and other dangerous natural phenomena;
- hydrological support of marine sectors of the national economy;
- the study of natural waters in natural hydrosynoptic situations and in conditions of anthropogenic impacts;
- rational use of water resources; conservation of biological diversity in the Caspian Sea region and adjacent territories; general and marine ecology.

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Bukharitsin Petr Ivanovich

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