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Aral Sea Ice Conditions in the Second Part of the 20th Century and Their Effect on the Bottom Topography

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ABSTRACT

Since the beginning of the second half of the 20th century, the water area of the Aral Sea has significantly changed, mostly due to anthropogenic causes. During a rapid level fall, started in 1960, its ice conditions also changed. Before 1960, the Aral Sea provided favorable conditions for ice scouring by ice hummocks. After 1960, the rapid level fall favored good preservation of ice gouges on the exposing bottom. However, the study of the scours on the exposed bottom of the Aral Sea using remote sensing methods along with the fieldwork provided the means to reconstruct a variety of mechanisms of the ice effect acted during sea level fall. It allowed to reconstruct ice conditions and mechanisms of the ice effect on the seabed. We found out traces of former multiple keels bottom scouring, repeated scouring while drifting along the winds and currents, marks of wind direction changes, grounded ice hummocks, scouring on the fast ice rim, etc. In the late 2000s, together with the critical decrease in the water area, the formation of ice hummocks diminished and ice effect on the Aral Sea bed ceased. Today, ice gouging is almost absent in the Aral Sea.

KEY WORDS: Aral Sea, ice conditions, ice gouging, bottom topography

INTRODUCTION

The Aral Sea is a famous example of human impact on the natural environment. However, Burr et al. (2019) demonstrated that sea level fluctuations occurred many times at least from the Late Pleistocene under the influence of runoff and evaporation variations. Changing sea level extent affected ice conditions of the Aral Sea. This study aims to show the ice condition change throughout the second part of 20th century and their influence on the seabed.

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 (Barnes et al., 1988; Ogorodov, 2011, etc). However, it can also affect the coasts and bottom of freezing seas and large lakes in mid-latitudes (Grass, 1984, etc.), in particular, Aral Sea. 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 hummocking (ridging) and formation of grounded hummocks (stamukhas) under the influence of hydrometeorological factors and coastal topography (Ogorodov, 2011). Ice gouging significantly changes bottom topography.

In this study, we characterize ice-gouging landforms at the Aral Sea bed, their origin and evolution along with a reconstruction of ice-gouging processes. 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.

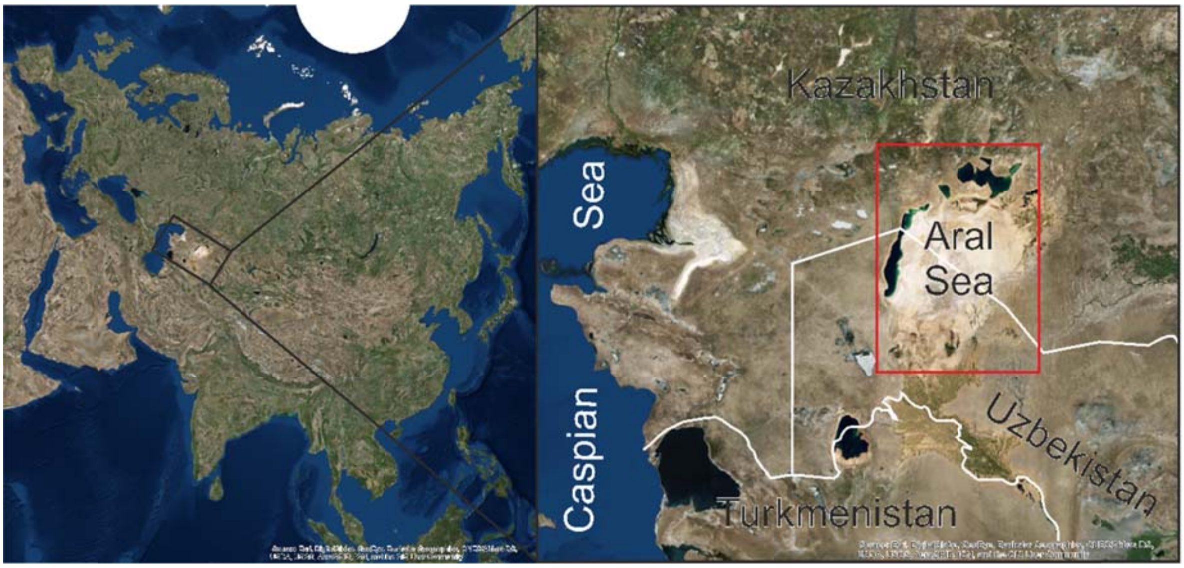

Figure 1. Study area. The red rectangle surrounds the territory of the Aral Sea during its greatest extent in the 20th century.

Before 1960 the Aral Sea was heavy used for fishery purposes and ice conditions of this period are well-studied. Ice conditions changed during sea level drop. A decrease in fishery significance led to a termination of ice conditions monitoring. After the sea level drop (Figure 2), the vast surface of the seabed was exposed to direct studies and remote sensing investigations. We studied the exposed Aral seabed by the both methods and documented ice-gouging landforms. Ice scours are the result of intensive impact of ice on the bottom during the sea level decrease. The study of ice-gouging landforms allowed to reconstruct the mechanisms of the effect of ice on the bottom.

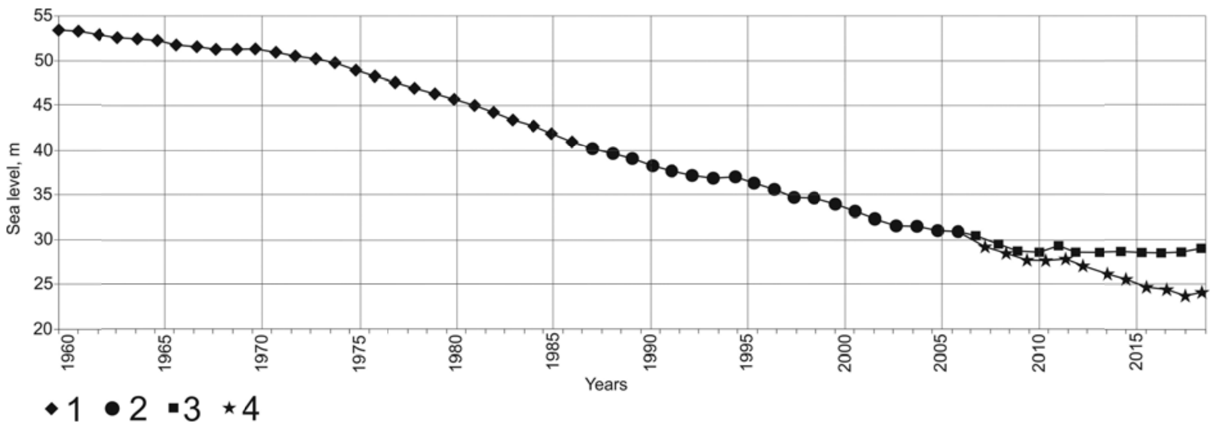

Figure 2. Fluctuations of the Aral Sea level in 1960-2018. 1–Aral Sea (1960–1986); 2–South Aral Sea (1986–2006); 4–East Aral Sea (2007–2018); 5–West Aral Sea (2007–2018).

Scours at the exposed bottom of the former Aral Sea were first discovered on aerial photographs by B. Smerdov in 1990 (published in 2008) from the Hydrometeorological Institute of Kazakhstan. 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. Recently we started detailed academic studies of ice gouging at the bottom of the Aral Sea.

Here, we use high-resolution satellite imagery along with field surveys to characterize ice gouging landforms and reconstruct the mechanisms of ice impact on the Aral Sea bottom. We also estimate main climatic drivers of ice gouging.

MATERIALS AND METHODS

Climate and Ice Conditions Review

The Aral Sea is located in an inland cold desert. The local summer is dry and hot; the winter is cold with unstable weather (Kostianoy & Kosarev, 2010). In November, air temperature in the northern part of the sea drops below zero; the average temperature of January is −11…−13 °C. In the southern part of the sea, the average temperature of January is −6…−8 °C. The period with negative temperatures lasts for 120–150 days (Bortnik & Chistiaeva, 1990). 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 cause 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…+10 °C.

Before 1960, water level in the Aral Sea was at the elevation of 53 m a.s.l. (above mean sea level). In 1961, it started to decline as a result of the flow redistribution of Syr Darya and Amu Darya rivers. 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. 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. Today, the water 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 (Schwatke et al., 2015, Figure 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‰ (Zavialov et al., 2012).

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), formation of rafted ice and hummocks often took place. Northerly and easterly winds pushed the ice to the southern part of the sea, causing its high concentration in the south. Ice started to melt in the second half of February and completely disappeared by the end of April (Bortnik and Chistiaeva, 1990). Thus, the ice conditions of the lake during its high water level position in the past were favorable for ice gouging.

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 melt began later and lasted longer. The 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 (Kostianoy and Kosarev, 2010).

Therefore, 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. Strong winds and presence of drifting ice for up to 6 months gives evidence of permanent movement of large ice fields. 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.

Remote Sensing Imagery Interpretation

For documentation of the 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 was subject to more detailed studies with analysis of the morphologic and morphometric parameters of the scours, their directions and distribution. We used WorldView, QuickBird, Sentinel, IKONOS, and GeoEye images taken from Bing, Yandex, Google websites and ESRI, 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. 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. 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 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, and grouped into intervals reflecting the degree of ice impact, in order to create a scheme of the whole former Aral Sea bed.

Previously Maznev et al. (2019) showed that the deciphered lines are traces of ice effects during higher level position of the Aral Sea. The parameters of the deciphered lines were used to reconstruct the mechanisms of ice effects on the bottom. This allowed us to discuss the diversity of ice formations existed on the Aral Sea in the second part of 20th century.

Field Investigations

During fieldwork conducted in October 2018 in the northeastern part of the East Aral Sea, 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. 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 the selected key and typical topographic points was measured to correct distances and elevations. The 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. 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.

RESULTS AND DISCUSSION

Ice Gouging Mechanisms Reconstruction

As a result of space images interpretation we found out several types of ice gouging landforms corresponding to different mechanisms of ice impact on the Aral Sea bed. Identically to ice gouges in well-studied 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 (Figure 3). In most cases, scours are multiple. 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 ground. Both single scours and their combs can be encountered on the Aral Sea bed. Such combs appear when a grounded hummock or stamukha plows the bottom with its multiple keels (Figure 4). These large ice formations are usually frozen into vast ice floes, increasing their weight and gouging force (Marchenko et al., 2007). The larger the ice hummock is, the more keels penetrate into the ground increasing the depth of the scours.

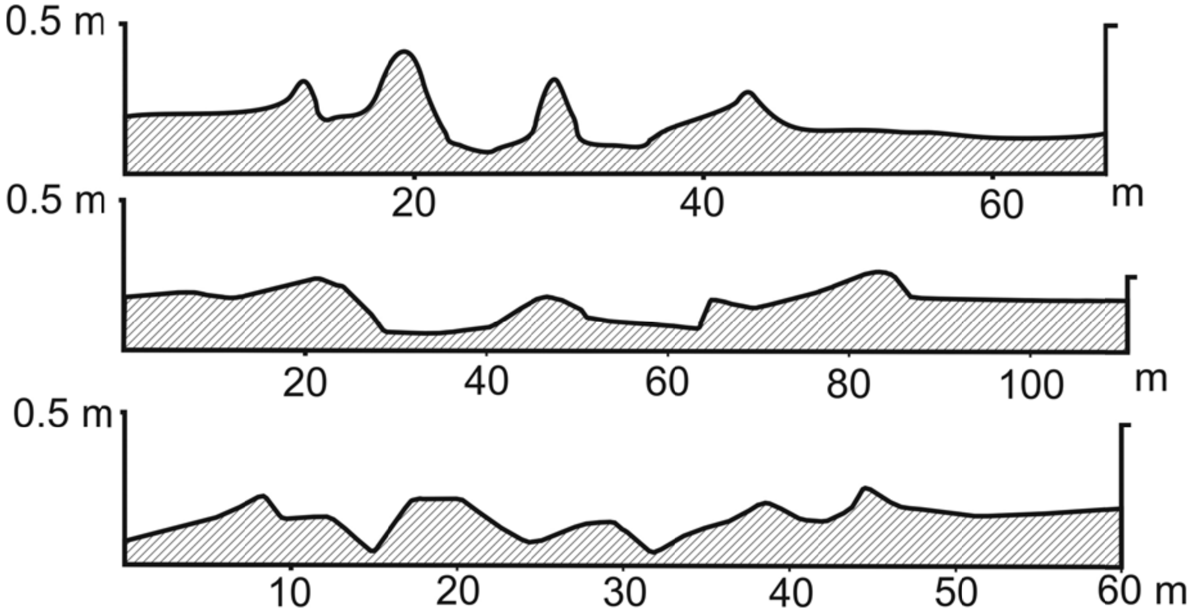

Figure 3. Cross-sections of ice scour taken from leveling survey

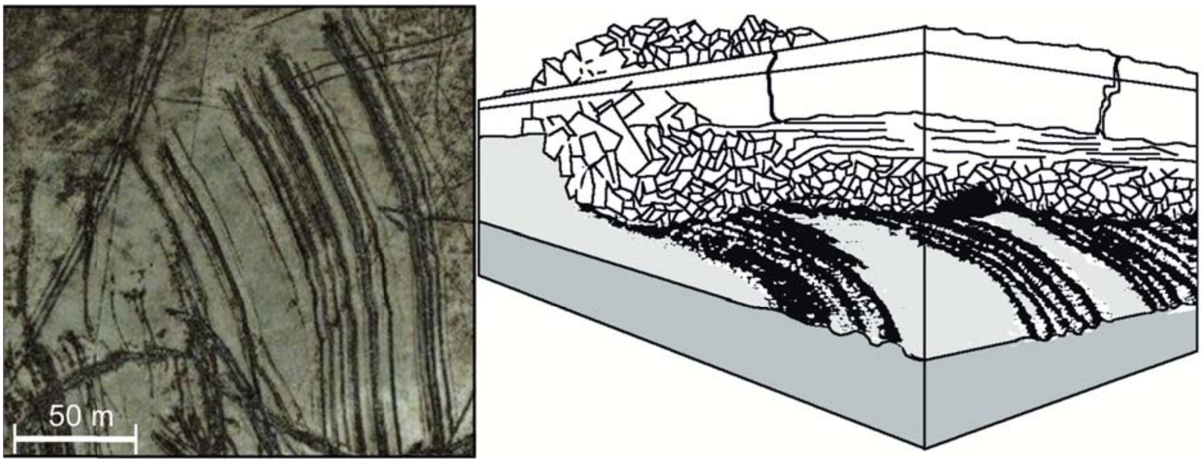

Figure 4. “Combs” of ice scours at the bottom of the Aral Sea (WorldView-3, left) and its formation mechanism (Barnes et al., 1988, right)

Another feature encountered at the Aral Sea is that both the ice scours and their combs are often imposed (Figure 5) as a result of their consequent formation (Ogorodov, 2011). One single ice hummock can create numerous scours of different directions cutting each other, as it drifts along the winds and currents.

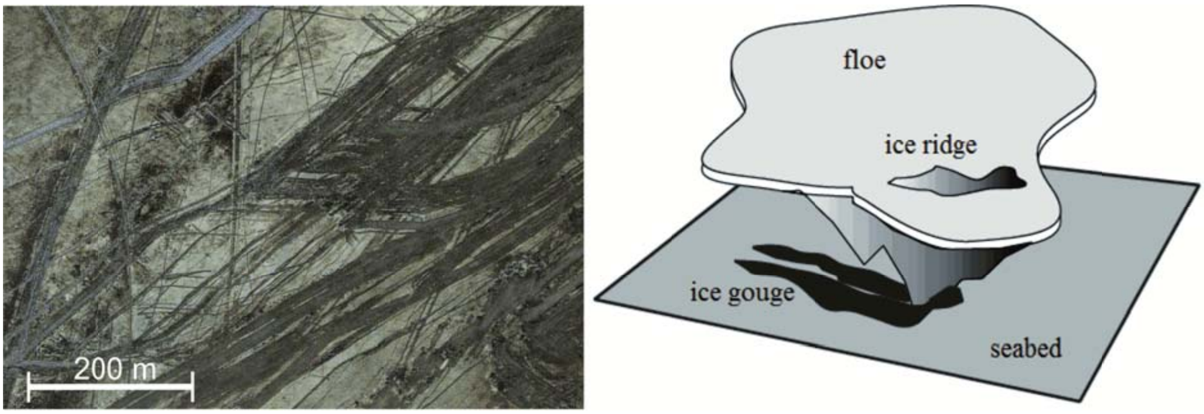

Figure 5. Imposition of ice gouging “combs” at the bottom of the Aral Sea (WorldView-3, left) and its formation mechanism (Marchenko et al., 2007, right)

The scours and ice gouges have bends 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 are typical ice gouging landforms as well (Figure 6). They appear when a large grounded at a shoal ice hummock (stamukha) is too heavy for the wind and currents to move it. Currents form specific topography round it, remaining after stamukha melting.

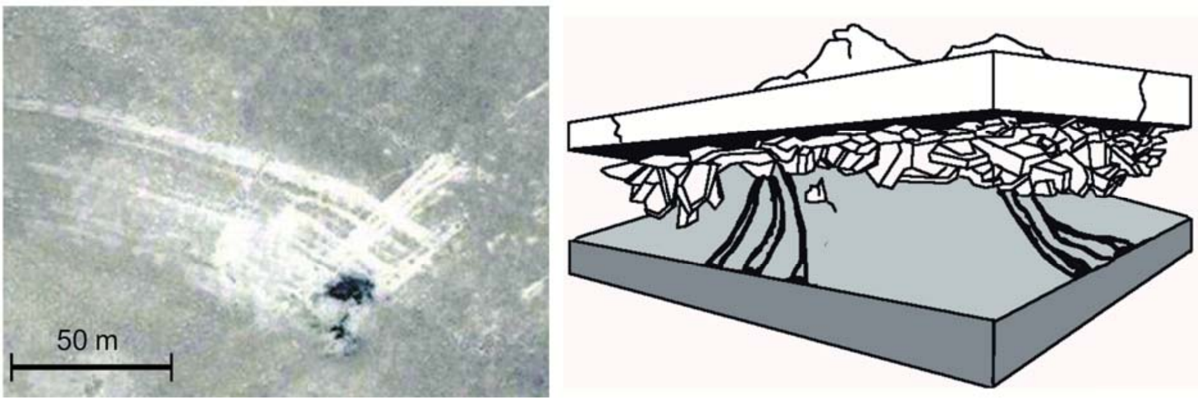

Figure 6. Stamukha pit at the bottom of the Aral Sea (WorldView-3, left) and its formation mechanism (Barnes et al., 1988, right)

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. Such mounds, typical for ice gouges of the different freezing seas were observed both in field and by remote sensing at the former Aral Sea bottom.

The morphometric parameters of the scours at the bottom of the Aral Sea are also comparable to the dimensions of ice-gouging landforms in other modern freezing seas and lakes. The ice gouges of Baydaratskaya Bay are presumably several kilometers long (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. The values for the Caspian Sea, Lake Erie and the Aral Sea are comparable, reaching several kilometers. The Aral Sea ice gouges are wide (to 15 m) in relation to other seas and lakes (Maznev et al., 2019). They are also shallower (0.2 m at the average) than the ice gouges of the Caspian Sea, Kara Sea and Lake Erie reaching ca. 1 m. 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.

In this way, the intensity of ice effect on the bottom in the Arctic seas and the Aral Sea is slightly different. However, beds of these seas are not scoured by ice hummocks of the same size, since the depth of the effects varies significantly. Typical ratio of the underwater and surface parts of the ice hummock is 1:5. The assumed depth of the most intensive ice effect in the Aral Sea is 2-5 m (Maznev et al., 2019). We suppose that thickness of ice hummocks rarely exceeded 6 m.

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 7) 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 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. A 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.

The distribution of the scours in the Aral Sea and their density patterns 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 and the Caspian Sea. 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 the 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 Aral Sea, most of ice gouges are concentrated in its flat central part.

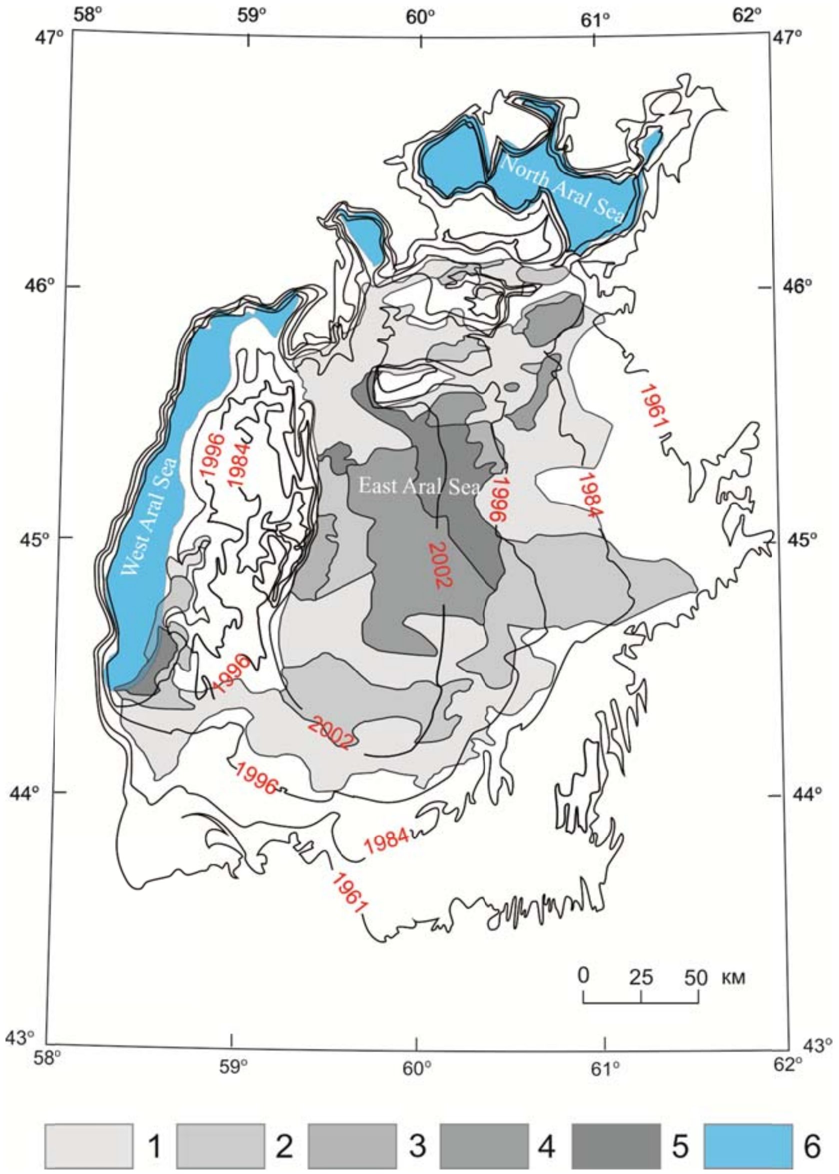

Figure 7. Estimated coverage of the Aral Sea bottom by ice scours: (1) <10% of ice scour coverage, (2) 10–20%, (3) 20–30%, (4) 30–50%, (5) > 50%, (6) modern Aral Sea water area. Background: contours of the former shorelines.

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.

Temporal Evolution of the Aral Sea Ice Conditions and Gouging Processes

Knowing the position of the retracting Aral Sea shoreline in space and time (Figure 7), 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, so it is unlikely that the ice effect on the bottom will intensify in the nearest future.

CONCLUSIONS

The ice-gouging processes on the Aral Sea are an outstanding example of ice effect on the bottom. In the second half of the 20th century, ice conditions changed along with the decrease in the water area. Before 1960, the Aral Sea provided favorable conditions for ice scouring by ice hummocks, but ice gouges were not preserved due to the wave action. Favorable conditions for ice scouring remained along with the sea level drop while at the same time conditions for better preservation of the ice-gouging topography were created on the gradually exposing bottom. Knowledge of ice conditions after 1960 has decreased. However, the study of the scours on the exposed bottom of the Aral Sea allowed to reconstruct a variety of mechanisms of the ice effect acted during sea level fall. In the late 2000s, together with the critical decrease in the water area, the formation of ice hummocks diminished and ice effect on the Aral Sea bed ceased.

ACKNOWLEDGEMENTS

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