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Influence of climate change on the ice regime of the Caspian Sea

Natalya Ivkina[1*], Zhanar Naurozbayeva[1], Bjørn Kløve[2]

[1]Republican State-owned Enterprise "Kazhydromet", Scientific-Research Center, Caspian Sea hydrometeorological research department, Republic of Kazakhstan
[2]Water Resources and Environmental Engineering Research Unit, Faculty of Technology, University of Oulu, Finland
*Corresponding author
Email address: ivkina60@gmail.com

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Abstract
Ice occurs in the Caspian Sea and its northern part influencing traffic, ports and the coastal region at large. Especially, heavy winds leading to massive ice jams considerably effect the socio-economic use of the sea. In recent decades, the Caspian Sea is affected by reduced water inflow from the major rivers and changes in climate, but these changes are not well documented or known. To better understand ice conditions, winter regimes and climate change impact, this article analyzes the cold periods from 1980 to 2016, in the northern part of the Caspian Sea and connects ice conditions to climatic characteristics. Winters are classified using the P.I. Buharitsin classification from sever to mild. The authors analysed changes in air temperature as of the main indicator of climate change, and a potential ice regime shift. The results show an annual warming of 1,1 ^{0}C and 1,3 ^{0}C for the cold period since 1990. Winter severity, which is closely linked to ice thickness has clearly decreased since the cold winters in 1950's and 1960's. Milder winters have changed ice conditions in the northernmost part of the Caspian Sea. A detailed analysis of mild and cold winters show a clear difference in ice depth, with thickness about 58 cm and 20 cm, respectively.

Keywords: temperature anomalies, ice regime, ice thickness, winter climate classification, Caspian Sea.

1. Introduction

The Caspian Sea, the largest drainless reservoir of the globe, located between Europe and Asia and called 'the sea' because of its sizes (Figure 1). In the northern Caspian Sea region, as well as in the whole of Kazakhstan, global warming is a concern. Potential impacts of climate change on the Caspian Sea include changes in ice accumulation and melting rate, which is closely linked to air temperature. This has several social, economic and ecological consequences.

During winter, the Caspian Sea is a partially frozen sea. In the northern part of the Caspian Sea, a steady and thick ice cover with complex dynamics is established annually. Here, the continental climate persists with long cold periods leading to stable ice formation [1, 2]. Further south and during spring thaw, ice and ice jams are formed interfering with sea traffic and navigation and damaging coastal hydraulic structures. Ice conditions have an impact not only on sea related economy, but also on an ecology of the sea and costal region.

Figure 1. Caspian Sea

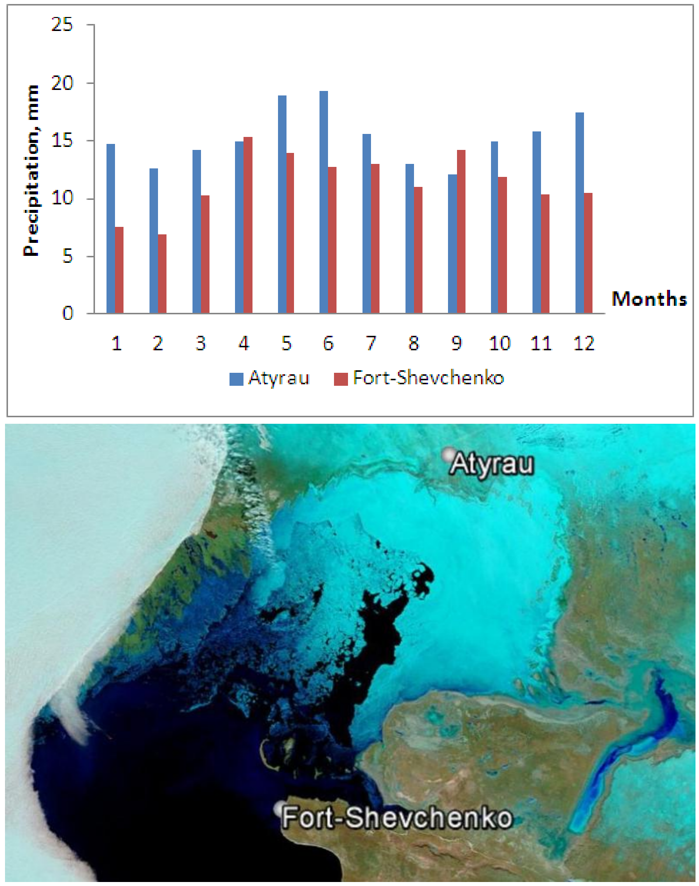
Shift in ice regimes (cover period) has an impact on biological cycles in marine ecosystems influencing, for example, fisheries and the Caspian seal. Therefore, identification of changes of ice conditions in connection with climate change is important.

The objective of the study is to connect sea ice depth, and extent and duration of ice cover to climatic and atmospheric changes, including natural and anthropogenic climate variability and change. The study focuses on the northeast part of the coast of Kazakhstan, where ice conditions are peculiarly sever. The authors use temperature anomalies in late autumn and winter to explain variation in sea ice.

2. Material and methods

2.1. Caspian Sea characteristics

The northern part of the Caspian Sea has a continental climate with warm summers (mean June-August is 24-25^{0}C in the North-East) and cold winters (mean December-February is minus 5-6^{0}C in the North-East). The precipitation regime varies considerably, depending on the interaction of air masses with the relief of the Caspian Sea coast. The amount of precipitation is low on the Caspian Sea eastern coast with an annual mean of about 100-170mm (Figure 2). The average annual precipitation here is not more than 95-125mm (slightly more in the Atyrau region - 173mm and Fort-Shevchenko - 172mm), while the seasonal variation is quite low, over years fluctuation in the amount of precipitation is considerable. In wet years, the precipitation depth can be 1,5 times higher than a long-term annual mean.



a)

b)

Figure 2. Monthly precipitation (a) at the Atyrau and Fort-Shevchenko meteorological stations (b)

The bathymetry of the Caspian Sea shows several partly isolated basins with different characteristics (Figure 3). The Kazakhstan region of the Caspian is divided into two parts: the eastern part of the Northern Caspian Sea (Atyrau Region) and the eastern part of the Middle Caspian Sea. The east part of the Northern Caspian Sea is shallow with an average depth of 2m (maximum only 8-10m). This half-closed reservoir has fairly low salinity as it is strongly influenced by the Volga and Ural (Zhayk) rivers flow. Water salinity in the Northern Caspian Sea varies from 0,2-2,0‰ (Volga River delta) to 9-11‰ in the depth part. In the Middle Part of the Caspian Sea salinity makes 13-15‰. The northern shallow Caspian basin is almost isolated from a direct influence of waters of the Middle Caspian Sea deep-water part which has an average depth of 200m (maximum up to 700m).

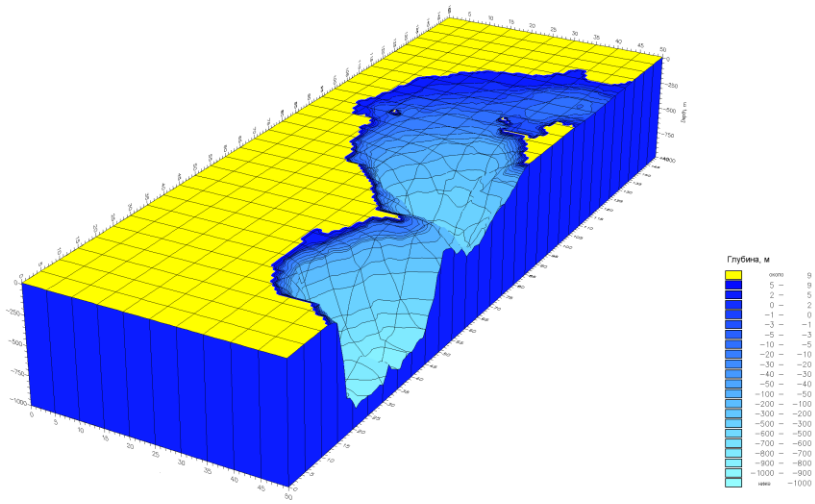


Figure 3. Bathymetry and the longitudinal cross-section of the Caspian Sea

2.2. Data and analysis of climate variation and ice regime

Daily air and water temperature data were obtained from the Caspian Sea hydrometeorological stations. These data were used to calculate air and water temperature anomalies and the difference-integral curve of mean annual air temperature. The curve was calculated as a temperature rate: $\Sigma(k-1) = f(t)$, an increasing sum of deviation from the mean annual coefficients of modular values of a number at the end of each year, Mi.

$$\frac{\Sigma(k_i - 1)/c_v}{N} \tag{1}$$

$$c_v = \sqrt{\frac{\Sigma(k-1)^2}{N}} \tag{2}$$

$$k = M_i / M_m \tag{3}$$

where M_i –value of a numerical series, M_m– mean value, N – number of cases. Mean temperature and changes for the periods 1990-2015 and 2000-2015 were calculated for 15 stations and posts in the Caspian Sea Region. P. I. Bukharitsin's classification [6, 7], which uses a sum of degree days of frost was used to analyze winter severity.

For the analysis of ice regimes the authors used data from Using data [8] to analyze changes in a sea ice cover: ice thickness, date of first shore ice formation, date of stable ice formation, start date of formation of stable shore ice, date of first ice formation, date of maximum ice thickness, most measured ice thickness, date of stable transition temperature at 0 ^{0}C in spring, maximum width of shore ice, first date of full freezing, final date of full freezing, date of occurrence of thaw holes, date of first break-in or shifts shore ice, first date of ice disappearance.

3. Results and discussion

3.1. Overview of Caspian Sea ice conditions

As the Caspian Sea consists of several basins with different salinity and climate (Figure 4), ice covers mainly the northern part of the Caspian Sea. Ice characteristics vary depending on wind and climate, forming solid and, even, ice and wind induced high ridges and hummocks.

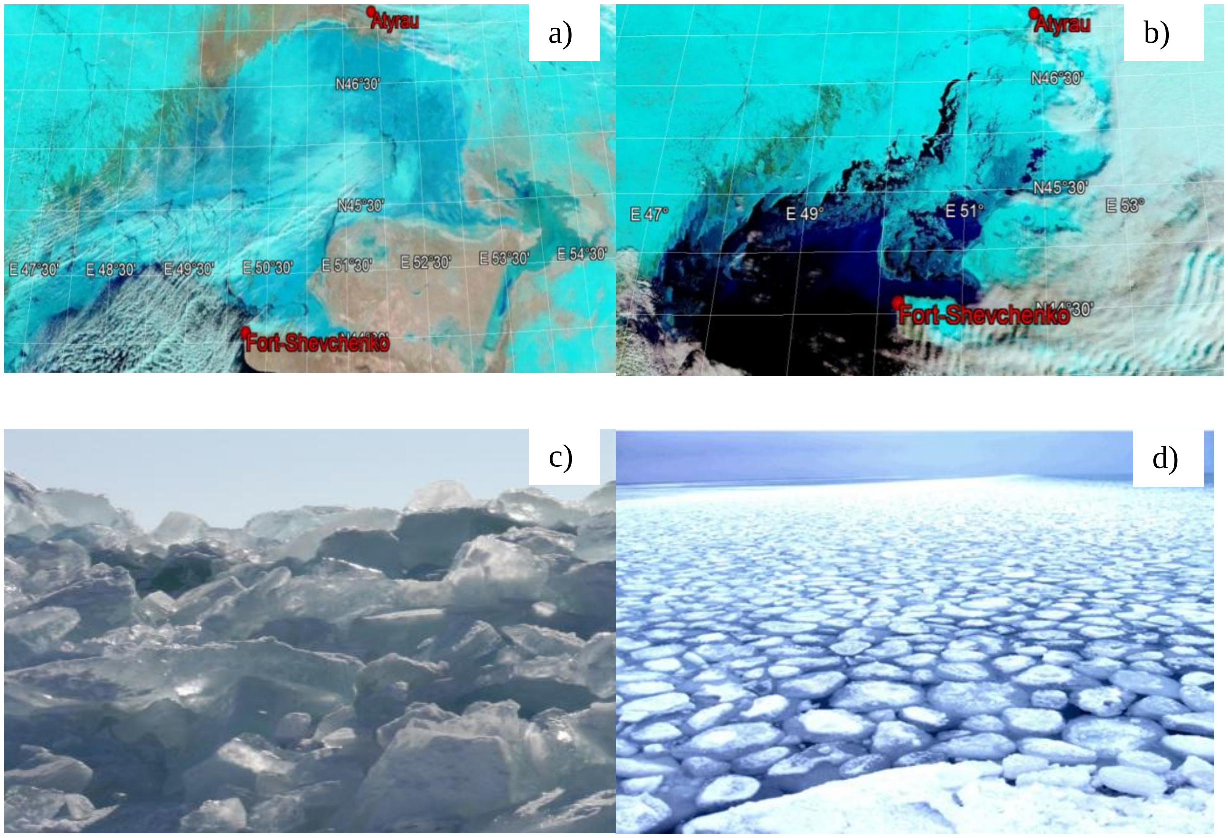


Figure 4. Ice conditions on the Caspian Sea a) cold winter 24th of January 2012 and b) Ice soft winter 30th of January 2016 (Image from the MODIS Rapid Response Project at NAGA/GSFC); show ice large ridges and hummocks (up to 10 m in height) c) and ice on the Northern Caspian Sea d)

In the northern Caspian Sea, ice formation starts in December-January depending on winter severity (Figure 5). In warm winters, ice appears in January leading to a low area covered with fairly shallow thickness of ice. The maximum thickness of ice occurs in February. In severe winters, an ice thickness can reach 50cm and a thick layer of ice is then typically observed from December till end of March.

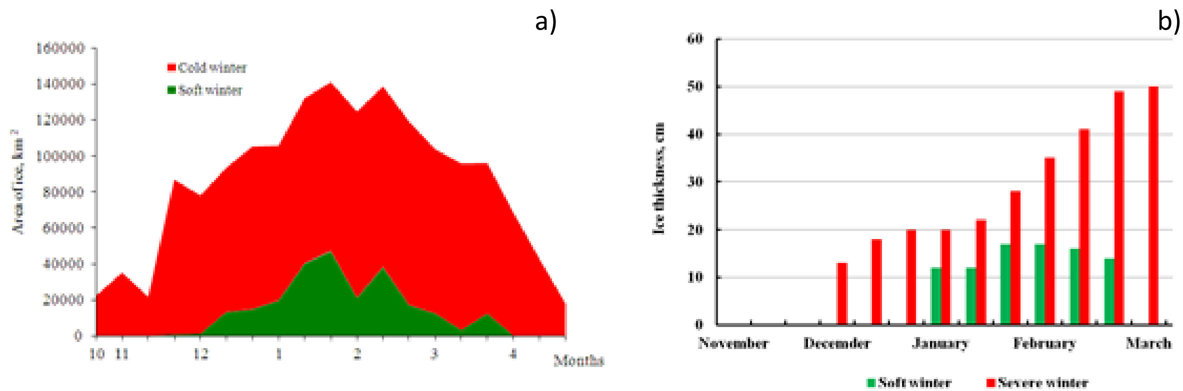


Figure 5. Ice conditions in mild and sever winters: a) area of ice at various winters and b) ice thickness in mild and severe winters

3.2. Climate warming

A trend of increasing air temperatures could be detected since the middle of the last century to the present times. Considerable warming could be observed in Kazakhstan since early 1990 for the Atyrau and Fort-Shevchenko metrological stations (Figure 6). This corresponds to the past research of Dolgykh and Petrova [3, 4], which shows that in the investigated area, as well as in whole Kazakhstan, the observed climate warming is on average of 0,34 ^{0}C per decade.

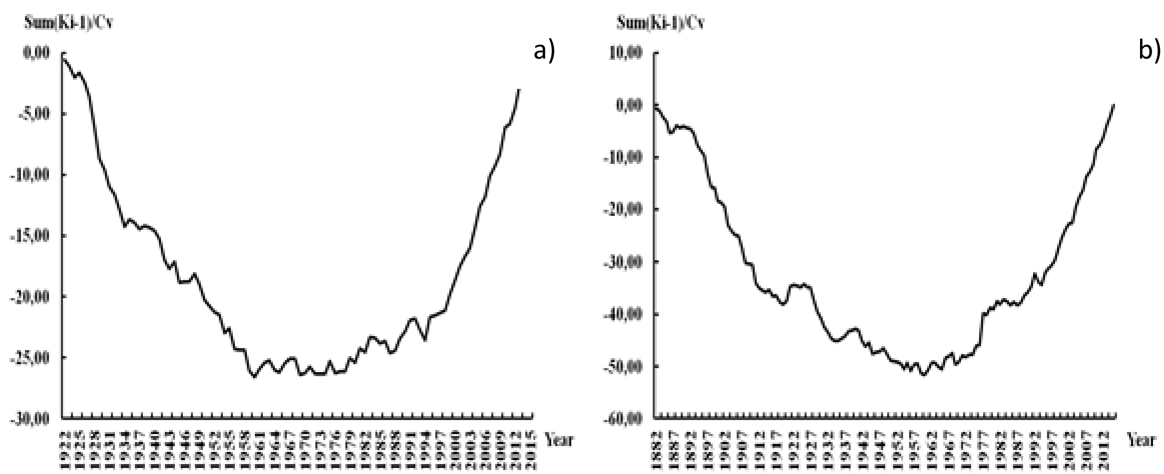


Figure 6. Difference-integral curve of mean annual air temperature at a) Atyrau Station for the years 1922-2015, and b) Fort-Shevchenko Station for the year 1882-2015

An analysis of 15 North Caspian meteorological stations show that the mean annual temperature has increased (Table 1) compared to the base period taken from the beginning of observations to 1989. The temperature rise during the period 1990-2015 compared to the base period was on average of 1,1 ^{0}C, and the temperature rise for 2000-2015 on average of 1,4 ^{0}C. For the cold period (November - March), the air temperature increased by 1,3 ^{0}C for 1990-2015 and by 1,6 ^{0}C for 2000-2015. The temperature increase during the cold period by more than the annual air temperature indicates that the recent warming might, especially, influence sea ice conditions.

Table 1. The average annual air temperature and the air temperature in the cold season compared to the base period (starting from 1989)

#		Annual air temperature (^0C)					Air temperature in the cold season (^0C) (November-March)				
	Meteorological Station	**(Tb) Base period**	**(T1) 1990-2015**	**(T1-Tb)**	**(T2) 2000-2015**	**(T2-Tb)**	**(Tb) Base period**	**(T1) 1990-2015**	**(T1-Tb)**	**(T2) 2000-2015**	**(T2-Tb)**
	Atyrau Region										
1	Atyrau	8,7	10,2	1,6	10,6	2,0	-4,8	-2,8	2	-2,4	2,4
2	Ganushkino	9,1	10,1	1,0	10,3	1,2	-3,2	-1,7	1,4	-1,6	1,6
3	Karabau	7,5	8,7	1,2	9,1	1,6	-6,7	-4,8	1,9	-4,3	2,4
4	Kulsary	9,0	9,8	0,8	10,4	1,4	-5,0	-4,0	1,0	-3,5	1,4
5	Makhambet	8,4	9,4	1,1	9,8	1,5	-5,0	-3,6	1,4	-3,3	1,8
6	Ushtogan	8,6	9,8	1,2	10,1	1,5	-4,5	-2,8	1,7	-2,5	2,0
7	Peshnoy	8,5	9,6	1,1	9,8	1,3	-4,5	-2,8	1,7	-2,4	2,0
	Mangistau Region										
8	Aktau	11,3	12,5	1,2	12,8	1,5	1,7	2,5	0,8	2,6	0,9
9	Akkuduk	12,0	13,0	1,1	13,3	1,4	-0,5	0,6	1,1	0,9	1,4
10	Beyneu	10,4	11,2	0,8	11,4	1,0	-3,0	-2,4	0,7	-2,1	1,0
11	Kulaly, island	10,7	12,1	1,4	12,1	1,4	-0,9	0,8	1,6	0,9	1,8
12	Kyzan	10,8	11,9	1,1	12,2	1,3	-1,6	-0,5	1,1	-0,4	1,3
13	Sam	9,3	10,4	1,1	10,7	1,4	-4,2	-3,2	1,0	-3,0	1,2
14	Tushibek	11,1	11,8	0,7	12,0	1,0	-0,6	0,2	0,8	0,4	1,0
15	Fort-Shevchenko	11,3	12,6	1,3	12,9	1,6	0,6	2,2	1,6	2,3	1,7

Trends in air temperature during a winter period were analyzed more detailed from 1961 to 2016 considering 55 cold periods. As seen from Figure 7, frequency of very severe and severe winters has decreased, and consequently during the last decades the frequency of moderate and mild winters has increased. Winters in the 60’s and 70’s were more severe with the amount of negative temperature sum closer to the maximum value observed.

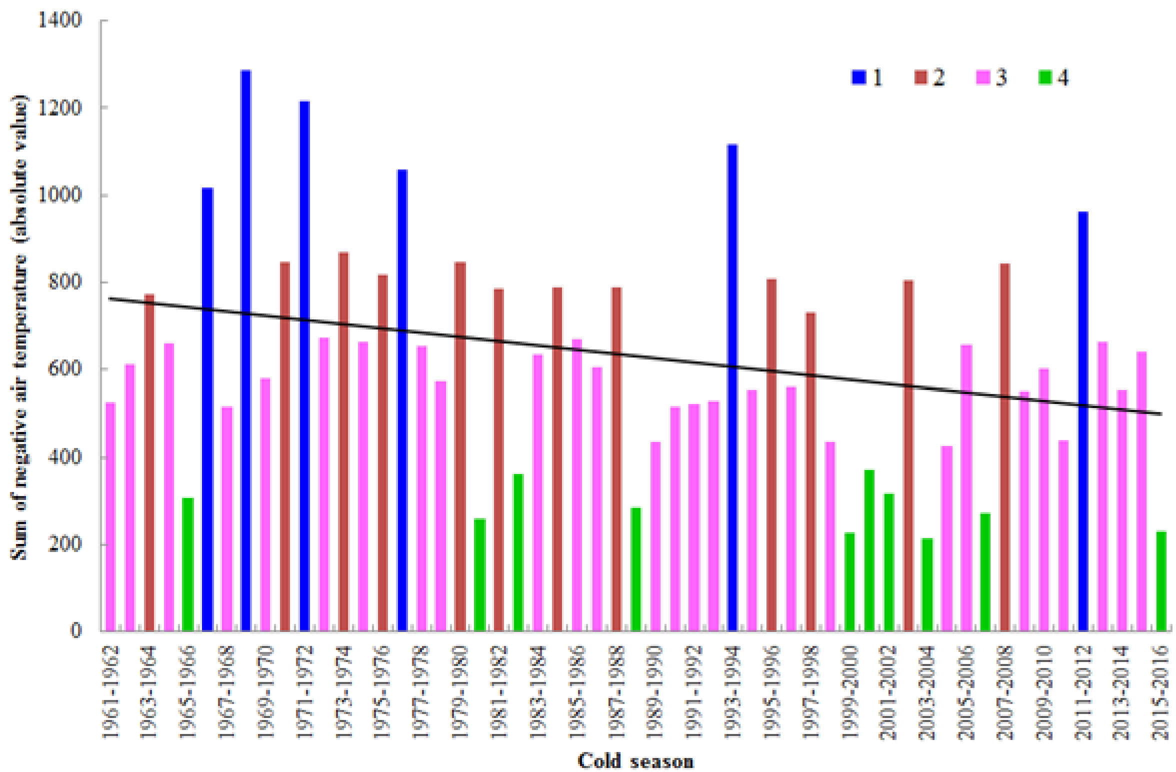


Figure 7. Sums of negative temperatures in the winter season (1961 - 2016), according to the Peshnoy Station. 1 - Very severe, 2 - Severe, 3 - Moderate, 4 – Mild

Ice thickness analysis for the period 1980-2016 reveals a large year to year variation in ice thickness and a steady trend of reduced ice thickness from 1981 to 2016 (Figure 8). Comparison of severe winters such as of 2011-2012 with mild winters such as of 2015-2016 and with sum of negative temperatures - 961,8 ^{0}C and - 230 ^{0}C, respectively, shows thicker ice in cold winters. Detailed comparison of these winters shows a later ice cover establishment for the mild winter 2015-2016, which corresponds to previous observations (tables 2 - 4). In sever winters, steady ice formation starts in November in the Northern part of the Caspian Sea and in the third week of January in the middle part of the Caspian Sea. In mild winters, ice was established in the northern regions in December, but in the middle part a stable ice cover was not observed. The thickness of ice during a severe winter reached 58cm in the northern part of the sea and 22cm in the middle part and during a mild winter ice thickness does not exceed 20cm in the northern part. Melting and disappearance of sea ice in the severe winter of 2011-2012 was observed later than in the mild winter of 2015-2016. Duration of the ice period of 2011-2012 was 156 days and the duration of the ice period of 2015-2016 was 98 days (almost two months shorter).

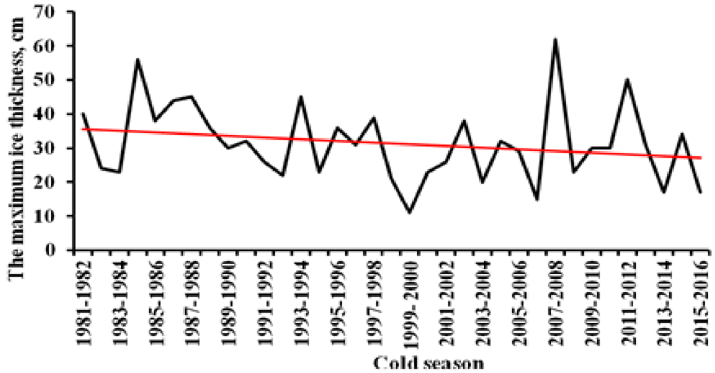


Figure 8. Maximum of ice thickness at the Peshnoy Station for the period 1981-2016

Table 2. Comparative characteristics of ice formation for the severe winter of 2011-2012 and the soft winter of 2015-2016

Station/ post	Period	Ice formation			
		Date of first ice formation	**Date of stable ice formation**	**Date of first formation shore ice**	**Start date of formation of stable shore ice**
Peshnoy	2011…2012	06.11.2011	06.11.2011	26.11.2011	26.11.2011
Zhanbay		20.11.2011	20.11.2011	22.11.2011	22.11.2011
Fort-Shevchenko		24.01.2012	24.01.2012	25.01.2012	not observed
Kulaly, island		24.01.2012	24.01.2012	25.01.2012	not observed
Aktau		30.01.2012	not observed	05.02.2012	not observed
Peshnoy	2015…2016	28.11.2015	10.12.2015	28.11.2015	30.12.2015
Zhanbay		21.12.2015	31.12.2015	21.12.2015	31.12.2015
Fort-Shevchenko		08.01.2016	not observed	not observed	not observed
Kulaly, island		03.01.2016	03.01.2016	03.01.2016	03.01.2016
Aktau		not observed	not observed	not observed	not observed

Table 3. Comparative characteristics of full freezing for the severe winter of 2011-2012 and the soft winter of 2015-2016

Station/ post	Period	Full freezing				
		Maximum width of shore ice, km	**First date of full freezing**	**Final date of full freezing**	**Most measured ice thickness, cm**	**Date of maximum ice thickness**
Peshnoy	2011…2012	0,1…0,5	26.02.2012	26.02.2012	50	06.03.2012
Zhanbay		more than 15	26.11.2011	26.11.2011	58	15.02.2012
Fort-Shevchenko		4-7	25.01.2012	not observed	22	13.02.2012
Kulaly, island		12,2	30.01.2012	not observed	9	13.02.2012
Aktau		0,1-0,5	not observed	not observed	10	08.02.2012
Peshnoy	2015…2016	0,1…0,5	30.12.2015	30.12.2015	17	02.02.2016
Zhanbay		more than 15	21.12.2015	21.12.2015	19	27.01.2016
Fort-Shevchenko		not observed	not observed	not observed	not observed	not observed
Kulaly, island		0,1-0,5	30.12.2015	30.12.2015	17	02.02.2016
Aktau		not observed	not observed	not observed	not observed	not observed

Table 4. Comparative characteristics of melting and destruction for the severe winter of 2011-2012 and the soft winter of 2015-2016)

Station/ post	Period	Melting and destruction		
		Date stable transition temperature at 0 ^0C in spring	**Date of occurrence of thaw holes**	**Date of the first break-in or shifts shore ice**
Peshnoy	2011…2012	20.03.2012	28.03.2012	02.04.2012
Zhanbay		20.03.2012	not observed	01.04.2012
Fort-Shevchenko		15.03.2012	not observed	16.02.2012
Kulaly, island		15.03.2012	not observed	01.02.2012
Aktau		27.02.2012	not observed	09.02.2012
Peshnoy	2015…2016	21.02.2016	26.02.2016	26.02.2016
Zhanbay		23.03.2016	not observed	07.03.2016
Fort-Shevchenko		not observed	not observed	not observed
Kulaly, island		not observed	not observed	02.02.2016
Aktau		not observed	not observed	not observed

A comparative analysis of air anomalies (Figure 9) showed that the severe winter of 2011-2012 on the investigated territory was significant, especially, in February. The anomaly reached 5-6 ^{0}C. The air temperature in February at the Peshnoy Station dropped to 30 ^{0}C below zero. April was also abnormally warm in the northern part of the Caspian Sea with the maximum anomaly value of 8,7 ^{0}C at the Peshnoy Station. For the warm year, the average monthly air temperature in February was +0,6 ^{0}C, whereas the mean annual mean value is -8,1 ^{0}C.

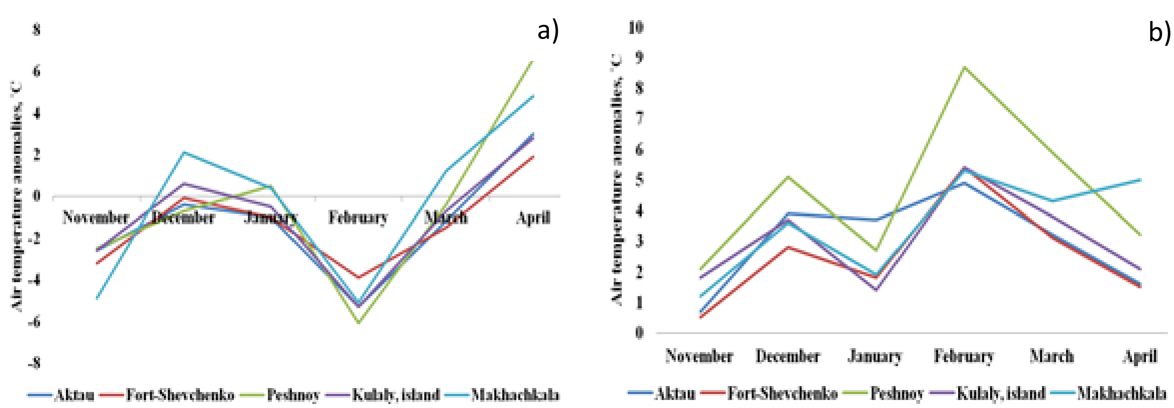


Figure 9 Time series of air temperature anomalies in a), the severe winter of 2011-2012 years and b) in the mild winter of 2015-2016

On Figure 10 are sea water temperature anomalies for the mild and sever winter. In the cold winter of 2011-2012, the water temperature in the middle of the Caspian showed a higher anomaly than in the northern part. November was very cold that facilitated a rapid establishment of an ice cover. February and March were cold with minimum water temperature of 0,3 and 0,7 ^{0}C, respectively. April was significantly warmer with air temperature reaching 22 ^{0}C, and average water temperature of 12 ^{0}C in the northern part. Intensive increase in air temperature in April facilitated the rapid warming of the surface water.

During the mild winter period 2015-2016, the water temperature exceeded the average long-term value by 1-1.5 ^{0}C. The maximum temperature recorded in March at the station Kulaly Island was 3,8 ^{0}C and in Makhachkala 3,7 ^{0}C.

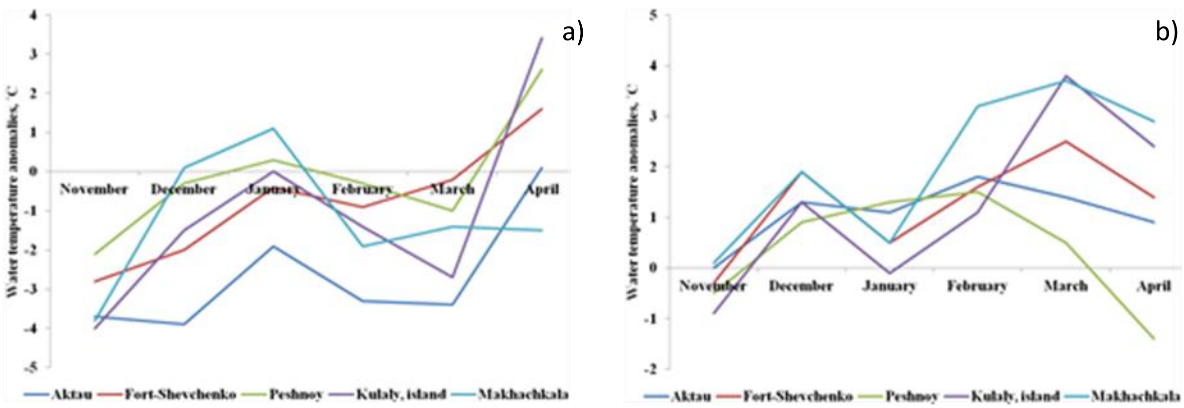


Figure 10. Time series of water temperature anomalies during a) the severe winter 2011-2012 and b) the mild winter 2015-2016

The further impacts of climate change on sea ice could be large and need to be further studied and a statistical significance of the detected trends further tested in a more detailed analysis. Ice cracks and splits increase with warmer climate. Lack of ice cohesion of could disrupt a habitat of Caspian species such as the Caspian seal. Other consequences and potential loss of ecosystem services provided by the Caspian Sea are needed to be analyzed, to assess mitigation measures for climate change impact.

4. Conclusion

The research shows that the ice regime of the Kazakhstan part of the Caspian Sea has been influenced by climate warming during the last decades. Air temperature has a positive trend. For all stations the recorded air temperature has risen compared to the base period. Changes in the characteristic of the ice regime have been observed as well. In particular, the date of occurrence of the first ice events has been delayed and the establishment of stable ice in the last decade occurred later. The disappearance of ice is observed to occur earlier. The obtained results indicated on increased occurrence of moderate and warm winters, and reduced occurrence of very severe winters. Also the duration of a winter period from 1980 to 2016 decreased.

5. Acknowledgements

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