Long-term monitoring of sea ice conditions in the Kerch Strait by remote sensing data

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ABSTRACT

The results of multi-year satellite monitoring of ice conditions in the Kerch Strait connecting the Black and Azov Seas are discussed. The issue gained importance in view of the ongoing construction of the Crimean Bridge across the strait. Our monitoring has been based on the whole variety of available satellite data including visible and radar data over the past 17 years. Every year the Azov Sea becomes fully or partially covered by ice during the cold season. In severe winters, ice often is carried to the Kerch Strait and even the Black Sea. An analysis of ice drift hydrometeorological conditions is presented. The ice conditions of 2017 are under special consideration. Everyday satellite monitoring of the Kerch Strait, including the construction area of the Crimean Bridge, revealed ice formation and drift features on the way from the Azov Sea through the Kerch Strait as well as ice interaction with the piers of the main and technological bridges under construction. It was found that, even under strong northeast winds, ice can pass neither through the piers, nor via the widest shipway. At present, it is hard to discern the impacts of the two bridges on floating ice, nevertheless when the construction is over and the technological bridge is gone, by all appearances the main bridge will strongly affect ice conditions in the Kerch Strait. This perspective calls for continuous satellite monitoring of the area that is enabled by cutting-edge systems and technologies.

Keywords: satellite data, SAR data, visible data, infrared data, ice conditions, wind, current, long-term monitoring, Kerch Strait, Crimean Bridge, Azov Sea, Black Sea

1. INTRODUCTION

Study of ice conditions in coastal zones of freezing seas is an important scientific and practical task. Changes in global climate have significantly affected ice formation dates, ice thickness and ice cover periods. Monitoring of ice conditions, as a rule, is performed using aerial and satellite instruments. Over the recent years, satellite monitoring has gained priority because of growing number of satellite sensors and increasing flow of high resolution data in broad electromagnetic wave range. Satellite monitoring of ice conditions is best organized for the Baltic Sea. Constant control of ice cover and its edges from first appearance to full and final melting is performed by Swedish Meteorological and Hydrological Institute and Finnish Meteorological Institute. Based on ship, coastal and satellite data, they regularly issue detailed ice charts. Ice charts of the whole Baltic Sea are published in autumn twice a week and daily when the amount of ice increases until ice breaks up in spring. The charts represent current ice situation, icebreaker positions and traffic restrictions in the Baltic Sea[1,2]. In Russia, similar charts are issued, although only weekly, by State Research Center "Planeta" (Planeta) of the Federal Service for Hydrometeorology and Environmental Monitoring of Russia[3]. The major drawback of Planeta's monitoring is that they use solely visible data (mostly Aqua MODIS) obtained in cloudless conditions, which by no means can ensure the required continuity of observation. In local applications, when the region of interest is not so large, it is reasonable to use multi-sensor monitoring techniques combining visible and radar satellite data.

The main goal of our work reported in this paper was to evaluate sea ice conditions in the Kerch Strait by way of a retrospective analysis of all available satellite data.

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Monitoring of ice in that region is crucial for practical reasons. The Kerch Strait connecting the Azov and Black Seas is a busy shipping route with several large ports. According to the transport management service of the strait[4], 11353, 10952 and 9969 ships passed via the Kerch Strait in 2013, 2014 and 2015, respectively[5]. An important ferry line connects Port Kavkaz (Krasnodarsky Krai) and Port Krym (Republic of Crimea) (Figure 1). Complex weather conditions aggravating with the appearance of ice and ship icing are serious problems for shipping in the strait. For instance, in mid-February 2017, a critical situation arose in ferry communication. For four days, 16-19 February, because of a sudden weather deterioration cargo ferries were unable to sail, two ferries stuck in ice so that two icebreakers were called in to free them. Monitoring of ice conditions gained much greater topicality with the start of construction of the Crimean Bridge (Figure 1). Going back in history, the first partly wooden railway bridge over the Kerch Strait was built in autumn 1944, just after the liberation of Crimea by the Soviet Army, but already in February 1945, three months after opening, it was destroyed by moving ice and then demounted. Strong northeast wind pushed ice to the Kerch Strait in 0.5 - 1 m piles and on 18 February 1945, 32 bridge piers that had no ice guards were destroyed. Interestingly, a few days before that accident, the bridge was used by the Soviet delegation on their way back from the Yalta Conference ended on 11 February 1945[6]. Although today's technology and materials enable building ice proof constructions, the knowledge of ice situation and ice drift prediction in the area of the Crimean Bridge is necessary to avoid rough consequences of complex meteorological conditions.

Studies of ice conditions in the Azov Sea and Kerch Strait began back at the turn of XX century. In the beginning, observations were conducted from coastal stations, later from ships and by aerial surveys. At the end of XX century, researchers started to interpret visible and infrared satellite data[7,8]. Here, we present results of complex satellite observations using both satellite aperture radars (SARs) enabling all-weather surveys, which is crucial for winter months with mostly total cloudiness above the Kerch Strait, and sensors providing high resolution visible data. The multispectral approach allows not only reliable detection of sea surface ice and ice type identification, but also high accuracy estimation of areas covered by ice. In particular, it is possible to distinguish sites of blocked ice and zones between the piers of the Crimean Bridge open for southward flow of ice.

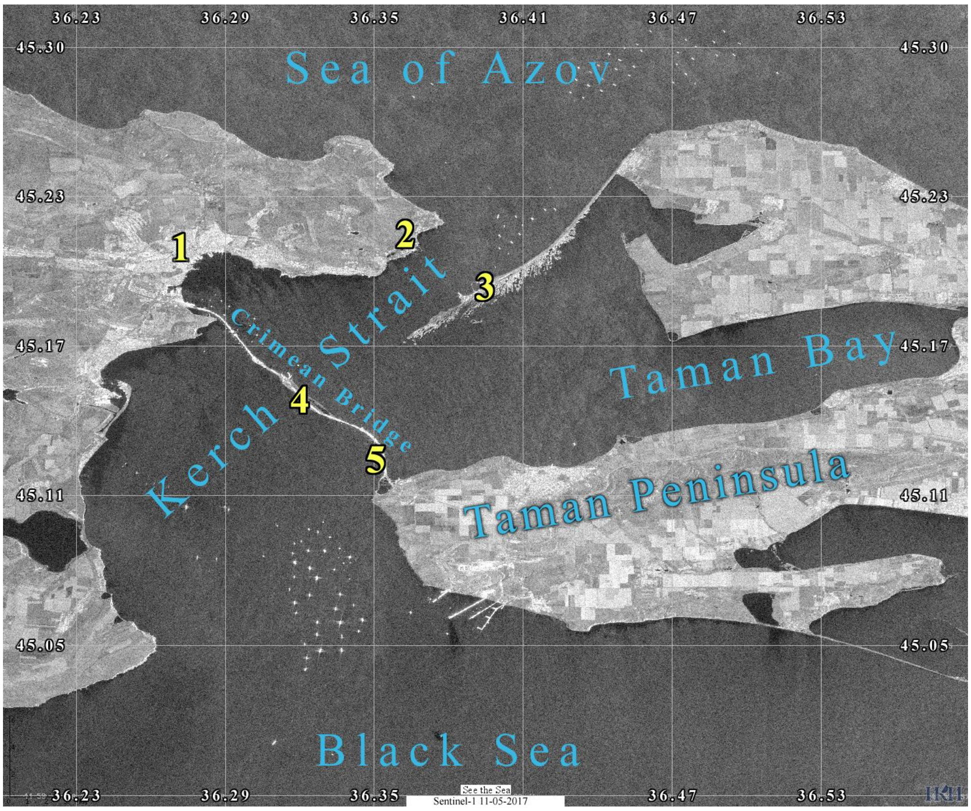


Figure 1. Georeferenced SAR-C Sentinel-1 image of the Kerch Strait of 11 May 2017. 1 – Kerch; 2 - port Krym (Republic of Crimea); 3 - port Kavkaz (Krasnodarsky Krai); 4 - Tuzla Island; 5 - Tuzla Dam.

2. STUDY AREA

The Kerch Strait connects the Black and Azov Seas (Figure 1). Its length is 40 km, width varies from 4.5 to 15 km. It is a shallow strait with average depth of 5-7 m and maximum depth of 18 m at its southern entrance. The hydrological regime is determined by the shallowness, water exchange between the two seas and meteorological conditions. Because of small depths, heating and cooling is rapid along the whole water column. Exchange between the Azov and Black Seas determines water salinity, density, transparency and color distributions. In the Black Sea, average salinity is only 18 ‰ due to distant connection with the ocean, massive river discharges, and limited exchange between water layers. The Azov Sea, the shallowest sea of the world, has even lower salinity of 10-12 ‰ because of the inflows of two large rivers: Don and Kuban. It is the most east and most freshened of all Atlantic seas. Water salinity in the Kerch Strait varies 12-15‰ due to the impact of the Azov waters. Wind is the major meteorological factor influencing the hydrological regime in the strait – waves, currents, storm surges and water mixing. As noted in[9], currents in the strait can be classified into three types (by water transport direction): Azov, Black Sea and, usually weak, varying currents. Sometimes, bidirectional currents, often well pronounced and with high velocity, can be observed. Current from north to south predominates, but it can reverse under strong south winds. Current velocity is 0.6-0.9 km/h on average, reaching 5.5 km/h under strong winds.

In October 2003, a dam, named Tuzla Dam was constructed between Tuzla Island and the Taman Peninsula. The dam width is comparable with widths of the three passages through which water is exchanged between the Black and Azov Seas. The effect of the dam on hydrological processes is discussed in[10,11]. The main conclusion is that under north wind, a cyclonic current occurs (from south to north) in the area between the dam and Tuzla Island. The dam affects ice drift as well.

Every year, the Azov Sea gets covered with ice, completely or partially. Small depth and heat content of the freezing sea determine the dependence of its icing regime on air temperature and, consequently, winter severity. Over nearly 120 years of observation, the duration of periods with severe, moderate and mild winters (absolute value of the sum of 24-hour temperature averages below zero is over 400ºC; less than 400ºC and over 200ºC; less than 200ºC, respectively) has been varying considerably. Today, with increasing air and water temperature averages we may expect less ice in the Azov Sea which does not rule out weather extremes associated with drastic air temperature drops and strong north winds.

3. DATA USED

The retrospective analysis of ice conditions in the Kerch Strait was performed for 1999-2017 winter-spring periods (December - March). The following datasets were examined.

SAR data:

- ERS-2 SAR (December 1999 - February 2011);
- Envisat ASAR (January 2003 - 8 April 2012);
- Sentinel-1A SAR-C (December 2014 - present);
- Sentinel-1B SAR-C (December 2016 - present).

Visible and infrared data:

- Envisat MERIS (January 2003 - April 2012);
- MODIS Terra/Aqua (January 2000 - present);
- Landsat-5 TM (December 1999 - April 2011);
- Landsat-7 ETM+ (December 1999 - present);
- Landsat-8 OLI/TIRS (December 2013 - present);
- Sentinel-2 A MSI (December 2015 - present).

Data analysis was performed using the toolkit of the See the Sea satellite information service developed at Space Research Institute of the Russian Academy of Sciences[12,13].

Meteorological parameters - air temperature, wind speed and direction – were obtained from the archives of local stations in Kerch and Taman. To assess the situation in January – February 2017, data from https://earth.nullschool.net/ were used. Results of satellite observations were compared with data available on the ESIMO site (http://193.7.160.230/web/esimo/azov/ice). Maps and descriptions on this site are based on data provided by coastal meteorological stations and satellite sensors and processed by Planeta. Ice maps for the Azov Sea and Kerch Strait (except for its south end) are in open access only beginning from the 2007-2008 season with just weekly updates. Since ice may exist in the strait for quite a short period, often less than a week, such information is hardly sufficient for ice conditions assessment.

4. RESULTS

4.1 Ice conditions in the Kerch Strait in 1999-2016

The results discussed in this section are obtained from a joint analysis of satellite and meteorological data, basically air temperature and wind field. Water temperature rapidly reflects air temperature variations due to strait shallowness.

In the Kerch Strait, ice usually first appears in the Taman and Kerch Bays and as fast ice along west coast. Our focus was on ice in the strait proper, except for the two bays. Since the satellite data archive for 1999-2000 is not representative enough (first Envisat data appeared in January 2003), the periods of ice existence cannot be estimated exactly for those years. Some additional information was found in literature[7].

In the cold season of 1999-2000, no ice was detected in satellite images, although throughout January, air temperature was below zero and north winds persisted. Perhaps ice lasted too short to be captured by satellite imaging of that time.

In the cold season of 2000-2001, a short lasting decrease of air temperature to – 3 … – 7°C at low northwest wind was observed in the 20s of December. Initial fast ice dated 20 December 2000. In warmer conditions (air temperature about – 2°C) but under strong, up to 11 m/s, east and northeast winds, ice was found almost everywhere across the strait. Maximum southward extent of ice was registered on 24th January 2001 along both coasts. Air temperature and wind variations are presented in Figure 2. The dates when ice was observed in the strait proper are marked blue. Ice formation under strong north and northeast winds is typical of the Kerch Strait. Another characteristic is that ice lasts shortly, it can appear and melt a few times during one season. Table 1 lists ice appearance dates and winter types for 1999-2016. We see that in the 2000-2001 cold season, ice clearance occurred twice.

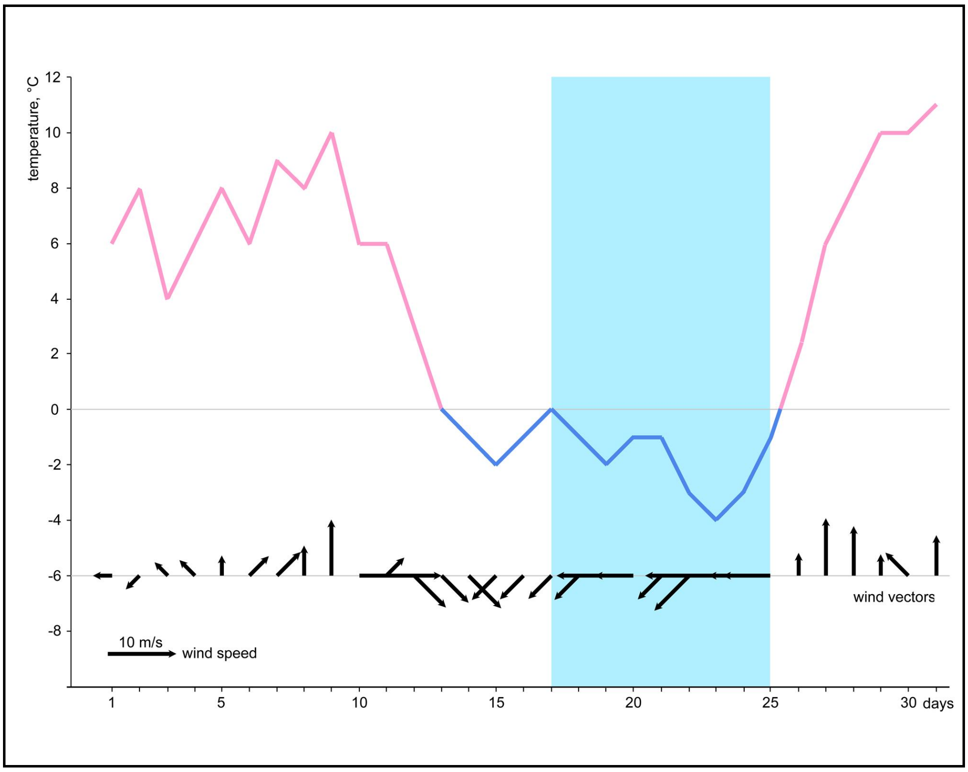


Figure 2. Meteorological conditions (air temperature and wind speed and direction) for January 2001. Blue area marks the days when ice was observed in the Kerch Strait proper.

Table 1. Main characteristics of ice seasons

Season	Winter type	Initial ice forms, date	Maximum southward extent of ice, date	Last ice clearance, date	Number of ice clearances per season
1999-2000	mild	-	-	-	-
2000-2001	mild	20.12.2000	24.01.2001	22 02.2001	2
2001-2002	mild	10.12.2001	21.01.2002	29.01.2002	2
2002-2003	moderate	19.12.2002	04.02.2003	28.03.2003	2
2003-2004	extremely mild	-	-	-	-
2004-2005	mild	05.02.2005	11.02.2005	18.02.2005	1
2005-2006	moderate (but the coldest)	09.01.2006	28.02.2006	04.03.2006	1
2006-2007	mild	-	-	-	-
2007-2008	moderate	30.12.2007	16.01.2008	21.02.2008	2
2008-2009	mild	01.01.2009	04.01.2009	13.01.2009	1
2009-2010	mild	25.01.2010	08.02.2010	16.02.2010	2
2010-2011	mild	19.01.2011	03.03.2011	11.03.2011	2
2011-2012	moderate	29.01.2012	16.02.2012	19.03.2012	2
2012-2013	extremely mild	-	-	-	-
2013-2014	moderate	25.12.2013	03.02.2014	17.02.2014	2
2014-2015	mild	-	-	-	-
2015-2016	mild	-	-	-	-
2016-2017	moderate	19.12.2016	13.02.2017	24.02.2017	3

Although the season of 2001-2002 was mild[7], according to Kerch station data, air temperature was recorded below zero already on 5 December, and remained negative till 17 January, sometimes reaching – 12 … – 15°C or rising above zero for a short time. The largest extent of ice cover was detected in an ERS-2 SAR image of 21 January 2002, when south edge of packed ice was near Tuzla Island, ice floes drifted between the island and west coast, along which separate ice formations were observed down to the Black Sea (Figure 3).

Winter of 2002-2003 was among the coldest in the 2000s. Air temperature went below zero on 1-2 December and remained negative till the end of February with short breaks. The date of ice cover onset could not be determined due to the lack of informative satellite data of the first half of December. According to Landsat-7 ETM+ data of 19 December, ice extended along the east side of the strait as far as Tuzla Island. From early March, day-time air temperature kept above zero, however, steady north wind that blew on 9 – 24 March drove ice all over the Kerch Strait. In a Landsat-7 ETM+ image of 25 March, ice cover distinctly extends from north to south down to the northern tip of Tuzla Island (Figure 4). So, the Kerch Strait had been covered with ice for almost four months with only short breaks (Table 1).

In the 2003-2004 season, negative air temperatures were registered only in February, wind was unstable and changed direction nearly every day. As expected, no ice was detected in satellite images.

The onset of ice cover in the mild season of 2004-2005 occurred in early February in conditions of strong, up to 15 m/s, east and northeast winds and air temperature drops to – 7°C at night. Maximum ice cover extension, to Tuzla Island and the newly constructed Tuzla Dam, was observed in an Envisat ASAR image of 11 February 2005 (not presented here).

Although the winter of 2005-2006 was the coldest of the previous 20 years, by the criterion of sum of negative temperatures, which amounts to 353.4°C, it belongs to the class of moderate winters. Negative air temperatures settled in early January and persisted practically till mid-February. Minimum daily average of –21°C (norm –0.6°C) was recorded at the Kerch station. Ice appeared on 9 January and remained at least till 18 February (by Envisat ASAR and ERS-2 SAR data). A color composite of Landsat-7 ETM+ data of 28 January 2006 in Figure 5a distinctly features packed ice in the Kerch Strait, at the north coast of Tuzla Island and along the strait's west coast. On the north of the strait, ice concentration varies, the ice is being driven by northwest wind southward from the Azov Sea.

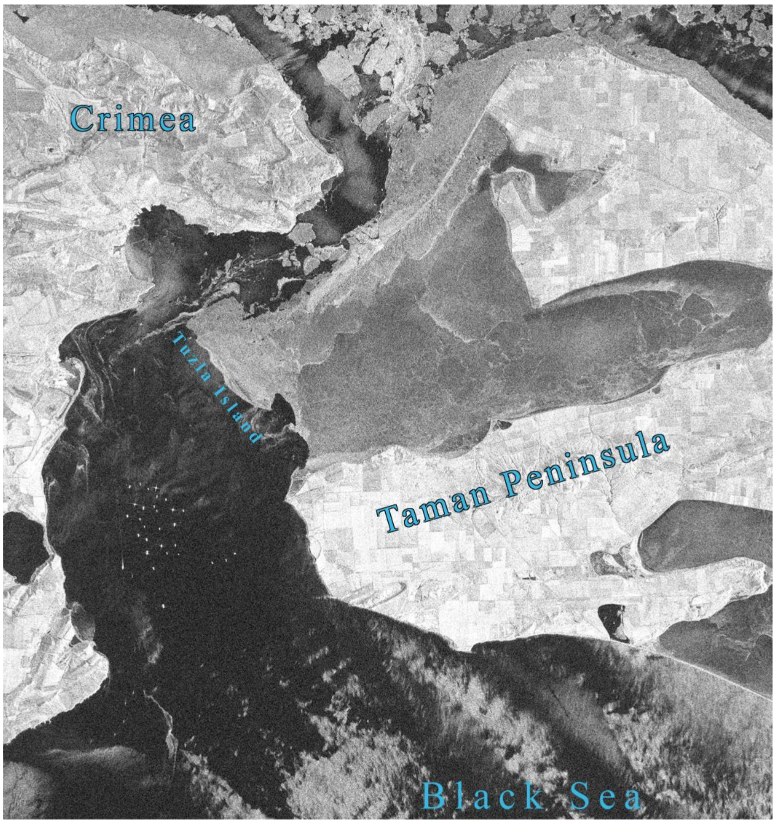


Figure 3. Ice cover in the Kerch Strait viewed by ERS-2 SAR, 21.01.2002 (VV polarization, pixel resolution 12.5 m).

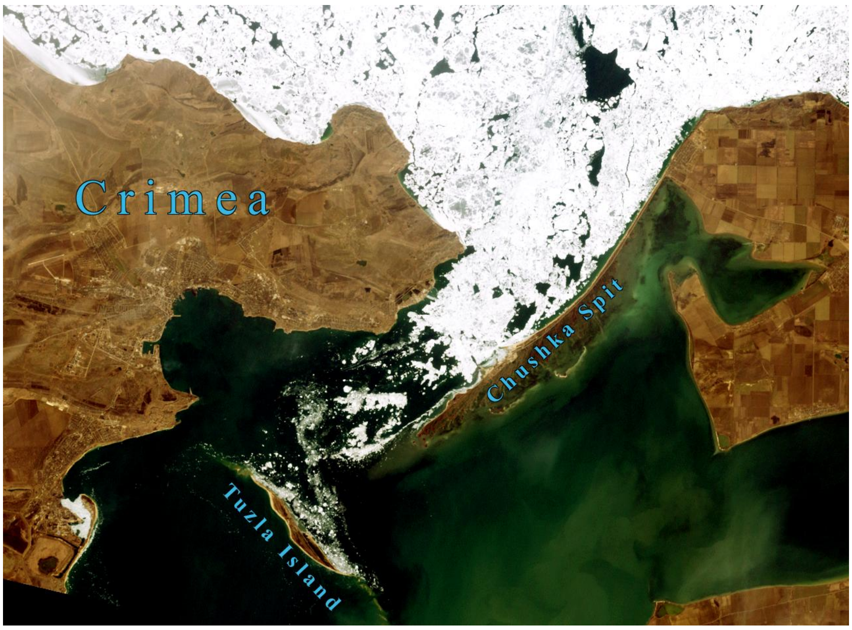
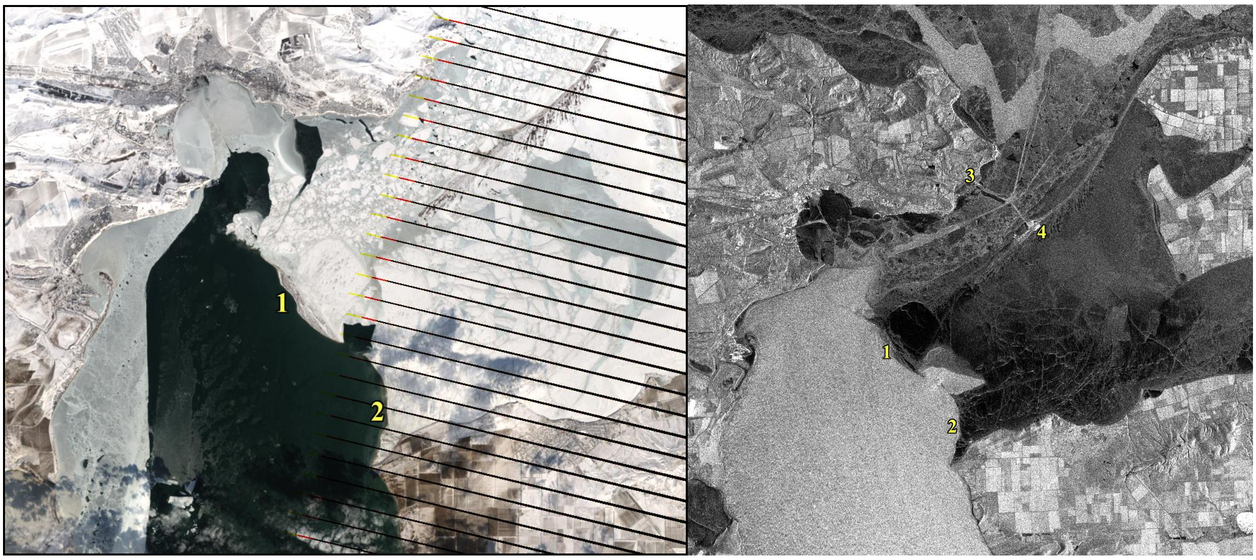


Figure 4. Ice drift from the Azov Sea through the Kerch Strait in northeast wind conditions. Landsat-7 ETM+ true color image, 25.03.2003 (pixel resolution 30 m).



(a) (b)

Figure 5. Ice cover in the Kerch Strait in 2006: (a) viewed by Landsat-7 ETM+, 28.01.2006 (resolution 30 m); (b) viewed by Envisat ASAR, 18.02.2006 (VV polarization, pixel resolution 12.5 m). 1 – Tuzla Island, 2 – Tuzla Dam, 3 – port Krym, 4 – port Kavkaz.

Ice conditions on 18 February 2006 are illustrated by an Envisat ASAR image (Figure 5b). Ice is still found as far south as Tuzla Island and the dam, but already absent along the west coast of the strait. Bright lines are clearly visible indicating icebreaker passages along the ship routes to the Azov Sea and between the Kavkaz and Krym ports.

During the mild winter of 2006-2007, negative air temperatures were recorded only from 22 to 27 February. No ice was detected in satellite data.

Starting 2008, the results of our satellite data analysis were compared with ice maps presented on the site of ESIMO (http://193.7.160.230/web/esimo/azov/ice).

In 2007-2008, winter was moderate with drastic weather changes. Two waves of cold were observed that determined two main periods of ice cover formation: from the end of December to 19 January and from 8 to 19 February 2008. Between these periods, south and southwest winds associated with passage of south cyclones brought a short rise of air temperature. Ice persisted only in bays as fast ice at the coast, Tuzla Island and the Dam, and floes drifting north. Maximum ice extent was detected in satellite data of 16 January (Envisat ASAR) and 19 February (Landsat-7 ETM+).

In the cold season of 2008-2009, ice was sparse in the Kerch Strait, with the exception of the bays. Ice appeared rather early, which is seen in ERS-2 SAR data of 3 January and Landsat-7 ETM+ data of 4 January, but it melted rapidly and did not form again practically for the rest of the season. This is explained by mostly cyclonic dynamics of the atmosphere and only short influence of anticyclones.

Ice formation in winter of 2009-2010 began only in the end of January which was evidenced by SAR, visible and infrared data. For the last time in the season, brash ice was detected on 8 February 2010 in ERS-2 SAR and Envisat ASAR images at positive air temperature and east wind. South ice boundary extended along the Tuzla Island – Dam line and the edge of fast ice at the strait's west coast.

In the 2010-2011 season, the intrusion of cold Arctic air masses was observed only in the last ten days of January, so ice formation began rather late. And ice was still found on the north of the strait in the first ten days of March, as evidenced by, for example, a Landsat-5 TM image of 7 March 2011.

Winter of 2011-2012 was moderate. According to Kerch station data, freezing temperatures were first recorded on 25 January and lasted till 20 February with the minimum of – 19°C on 2 February. Wind was mostly northeast, with gusts up to 20 m/s in February. Ice cover began to form on 29 January, reaching maximum extension by mid-February. Images of Envisat ASAR of 10 and 16 February 2012 demonstrated that ice floes were found even in the Black Sea pre-strait area. In February 2012, ice propagated farthest south since 2000. The second wave of cold was in March, the ice cover lasted till 17 March (Landsat-7 ETM+ data).

Because the Envisat mission ended in April 2012, monitoring of ice conditions in the end of 2012 and in 2013-2014 was performed using optical satellite data only.

Winter of 2012-2013 was very warm, air temperature kept above zero, except for short 3-day periods in the beginning of January, no ice cover in the Kerch Strait was detected throughout the whole season.

In winter of 2013-2014, two waves of cold were observed: in mid-December, when air temperature remained below zero for four days, and from 13 January to 11 February. During the first wave, ice was detected in visible images (for example, Landsat-8 OLI of 25 December) only in the Dinskoy Bay (east of Chushka Spit). During the second wave, when air temperature below – 10°C kept from 30 January to 3 February (minimum – 15.4°C on 31 January) and speed of northeast and east-northeast winds reached 19 m/s in gusts, the extension of ice cover was the greatest over the whole 1999 - 2017 observation period[14]. Figure 6 presents a color composite Landsat ETM+ image of 3 February 2014. The area of ice cover in the strait proper, excluding the Taman Bay, was over 290 km^2. Note that on the north of the Kerch Strait, initial ice forms and nilas as well as floes drifting from the Azov Sea prevailed, while on the southeast, primarily concentrated (at the coast) and drifting ice was observed. And in the area to the west of Tuzla Island, ice freely drifted south.

During the mild winters of 2014-2015 and 2015-2016, negative air temperatures were not recorded, except for short periods in January and in February. Insignificant fast ice was observed only along the Chushka Spit and in the Taman Bay.

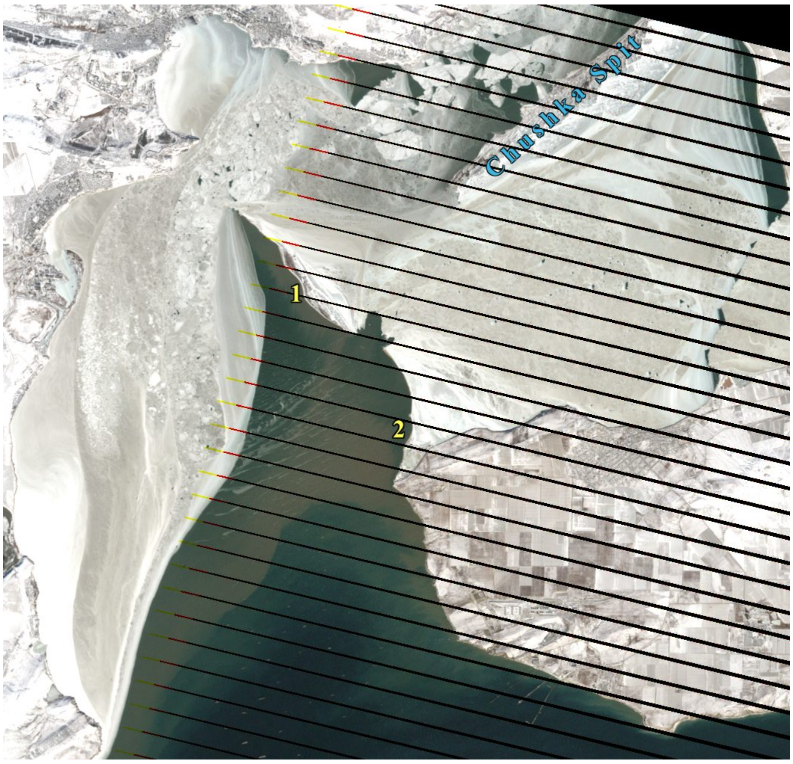


Figure 6. Free drift of ice in the western part of the Kerch Strait. Landsat-7 ETM+ color composite image, 03.02.2014, (resolution 30 m). 1 – Tuzla Island, 2 – Tuzla Dam.

4.2 Ice conditions in the Kerch Strait in winter of 2016 – 2017

In winter of 2016-2017, the intrusion of Arctic air masses began as early as mid-December. Starting 16 December 2016, night-time temperature dropped to - 6°C. Under northeast wind conditions, formation of ice started on 19 December and continued till 26 December on the north of the strait along Chushka Spit and in the Taman Bay. The next cold period occurred from 25 January to 1 February 2017 and featured air temperature drop from above zero to -5…-11°C and north winds of 5-10 m/s. This resulted in rapid water temperature decrease and formation of new ice. In a Sentinel-1A SAR-C image of 30 January (Figure 7), ice floes north of Tuzla Island and Dam are clearly visible as well as fast ice along the southwest coast. The image was acquired under 11 m/s northeast wind and air temperature of – 8°C (Figure 8).

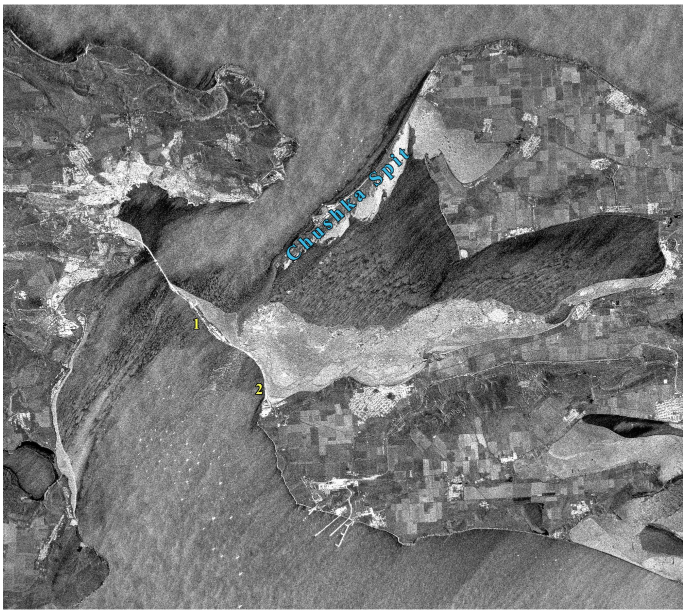


Figure 7. Ice cover during second wave of cold. Sentinel-1A SAR-C, 30.01.2017 (VV polarization, pixel resolution 9.8 m). 1 – Tuzla Island, 2 – Tuzla Dam.

In the area to the west of Tuzla Island and between the dam and the island, where the construction works are underway, ice oozes through the bridge piers and drifts southwest (Figure 7).

On 2-3 February, a south cyclone brought warm weather and air temperature rose to +9°C (Figure 8). According to satellite data, almost the whole of the Kerch Strait, except the western part of the Taman Bay, was freed from ice[15].

Over the next week, the situation had changed dramatically. The third wave of cold, from 7 to 16 February, came with air temperatures between -3…-6°C and north winds of 5-13 m/s. In a few days, practically the whole northern part of the Kerch Strait was covered with ice. Figures 9a and 9b present Landsat-7 ETM+ and Sentinel-1A SAR-C images obtained on 11 February with time interval of 7 hours and in conditions of northeast winds of 9-10 m/s (Figure 8).

In the color composite image, we can see that the north of the strait is occupied by drifting ice with only narrow band of free water at the west coast. Ice concentration increases as one approaches Tuzla Island and the bridge under construction. South of the island, the water surface is mostly free of ice, with some fast ice along the coastline. The increased ice concentration north and its absence south of the Crimean Bridge may imply a diking effect produced by the bridge construction elements[14]. The passage of ice through the piers of the main and technological bridges is virtually blocked and the whole ice mass is pressed against them. A special focus is on two zones where ice oozes south through the barrier. They are indicated by arrows in the figures. Note that much less ice goes through the relatively wide shipway of the bridge compared to the amount of ice oozing on the left and right of the shipway and at the southeast end of the bridge, between the dam and Tuzla Spit. At the bottom of Figure 9a, a sharp boundary is quite distinct between the Azov Sea waters flowing through the Kerch Strait and waters of the Black Sea.

Ice plumes near the shipway and at the southeast end of the Crimean Bridge can be clearly seen in a SAR image presented in Figure 9b. Their areas are estimated at 0.25 and 9.1 km^2, respectively. In the south, a large number of ships are waiting for icebreaker aid on their way to the Azov Sea via the Kerch Strait.

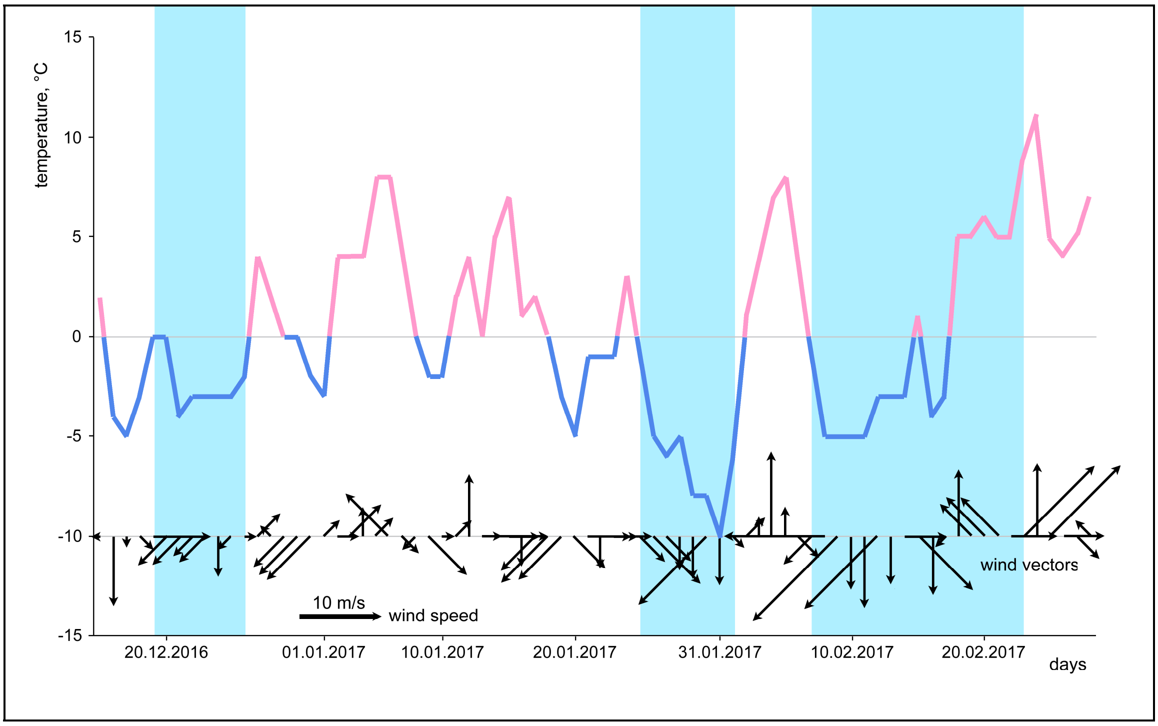
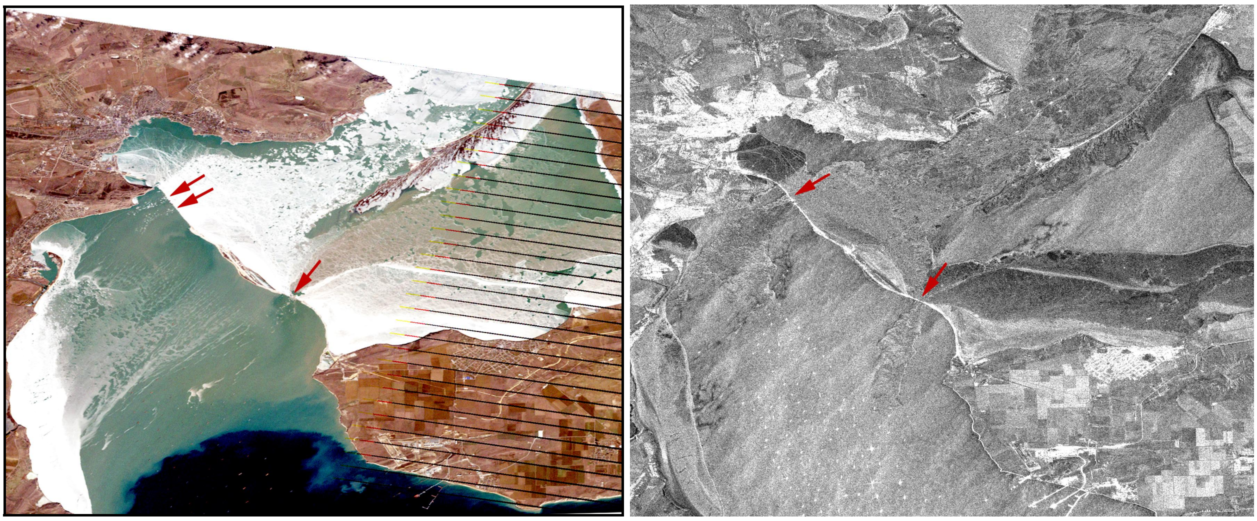


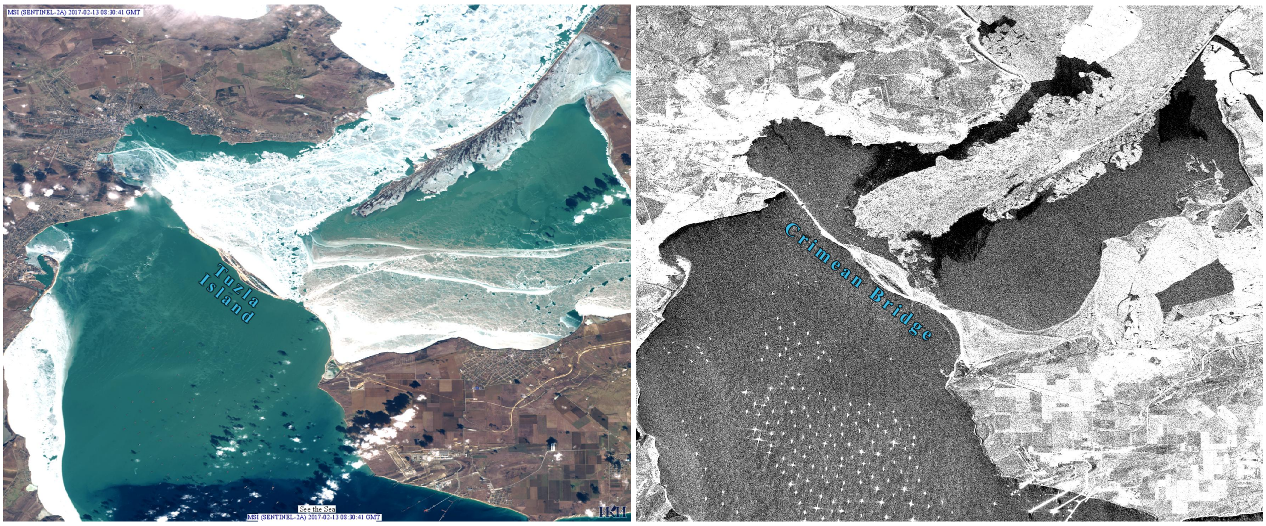
Figure 8. Meteorological conditions (air temperature and wind speed and direction) in the 2016-2017 cold season. Blue areas mark the days when ice was observed in the Kerch Strait proper.



(a) (b)

Figure 9. Ice cover in the Kerch Strait on 11 February 2017: (a) Landsat-7 ETM+ color composite image, 08:21 UTC, (VV polarization, pixel resolution 30 m); (b) Sentinel-1A SAR-C, 15:27 UTC (pixel resolution 9.8 m). Arrows indicate the zones where ice oozes south.

By mid-February, because northeast winds still persisted, ice conditions had aggravated and the ice cover grew to its maximum. Figure 10 presents a color composite Sentinel-2A MSI image of 13 February; the meteorological parameters at the moment of image acquisition were: 6.4 m/s northeast wind, T = -3°C. North of Tuzla Island and the bridge, areas with ice concentration of 10 units are well pronounced, while south of the bridge, ice-free water surface is prevalent. The boundary between the Azov and Black Seas' waters has shifted south, and no more ice oozing south of the bridge is observed.



(a) (b)

Figure 10. Ice cover in the Kerch Strait viewed by: (a) Sentinel-2A MSI color composite image, 13.02.2017 (pixel resolution 10 m); (b) Sentinel-1B SAR-C image, 16.02.2017 (VV polarization, pixel resolution 9.8 m).

Satellite data obtained on 16 February (Figure 10b) showed that the area of concentrated ice retreated north off the bridge and Tuzla Island and its dimensions decreased.

The history of meteorological parameters for 13 – 16 February evidences that the main reason for the retreat was wind change to westerly on 14 February and associated warming. The intrusion of warm air mass was coupled with strong 7-8 m/s wind (gusts up to 12.5 m/s) which also contributed to breaking and eastward drift of the ice.

We may state, based on satellite data obtained in February 2017, that the construction of the Crimean Bridge significantly affects ice cover dynamics and propagation regime in the Kerch Strait.

According to in situ observations and modeling of ice evolution and concentration dependencies on wind direction and blowing duration reported in literature[16,17,18], ice can drift all the way from the Azov Sea through the Kerch Strait down to the Black Sea under the influence of moderate and even weak northeast winds.

5. CONCLUSIONS

Summing up the results of satellite observations of ice conditions in the Kerch Strait in 2000 – 2017, we can draw the following conclusions.

In the Kerch Strait, as a rule, ice first appears in the Taman and Kerch Bays and as fast ice along the west coast of the strait and at the north coast of Tuzla Island. In cold winters under strong north and northeast winds, ice can be carried as far as the Black Sea. In the 2000s, winters in the area of the Azov Sea and Kerch Strait have become colder, compared to the last 50 years of XX century. The coldest were the winters of 2002-2003, 2005-2006, 2007-2008, 2011-2012, 2013-2014, 2016-2017. However, there were no extremely severe winters (with absolute value of the sum of 24-hour air temperature averages below zero exceeding 400ºC). Ice formation basically occurred at later times, late January – early February. In 2012, ice in the Kerch Strait was found till mid-March. In conditions of decreasing air temperature and strong northeast and east winds, ice occurs rapidly, and it equally rapidly melts in the strait proper (not in the bays) with intrusion of south cyclones. As a rule, during one winter several waves of cold are recorded, and each may cause ice formation.

Construction of the Crimean Bridge gave an added topicality to monitoring ice conditions in the Kerch Strait. Everyday satellite monitoring in January – February 2017, including the construction area, revealed the peculiarities of Azov Sea ice formation and drift through the strait as well as its interaction with the piers of the main and technological bridges. We found that even under strong northeast winds, ice could not overpass the construction site, including the wide shipway. The technological bridge appears to be a giant dike hampering southward drift of ice. It is not clear yet if this effect will persist when the construction is completed and the technological bridge removed. Anyway it is obvious that ice conditions in the Kerch Strait should be closely monitored using satellite instruments and techniques[15].

We do not know whether this effect was foreseen and taken into account at the bridge design stage, nor what kind of modeling was performed and estimates obtained. Perhaps not only daily monitoring of ice conditions is required, but some modification of pier design as well, such as ice guards. In severe winters, because of the diking effect of the bridge, ice ridges and stamukhi can appear in shallow waters and cause additional problems for bridge operations.

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