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Journal of Marine Systems 47 (2004) 89–100
JOURNAL OF MARINE SYSTEMS
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Sea ice cover in the Caspian and Aral Seas from historical and satellite data

Alexei V. Kouraev[a,b,c,*], Fabrice Papa[d], Nelly M. Mognard[a], Petr I. Buharizin[e], Anny Cazenave[d], Jean-Francois Cretaux[d], Julia Dozortseva[f], Frederique Remy[d]

[a] Centre d'Etudes Spatiales de la Biosphère (CESBIO), BPI 2801, 18, Ave. E. Belin, 31401 Toulouse Cedex 4, France
[b] State Oceanography Institute, St. Petersburg Branch, St. Petersburg, Russia
[c] Nansen International and Remote Sensing Centre (NIERSC), St. Petersburg, Russia
[d] Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), Toulouse, France
[e] Water Problems Institute of Russian Academy of Sciences, Astrakhan Division, Astrakhan, Russia
[f] Hydrometeorological Centre of the Caspian Fleet, Astrakhan, Russia

Received 7 May 2003; accepted 31 December 2003

Available online 14 March 2004

Abstract

Time and space variations of ice cover in the Caspian and Aral Seas from historical and satellite data are discussed. Existing published continuous time series of ice cover parameters for these seas stop in 1984–1985; the results of observations for later periods are heterogeneous and mostly unpublished. The current lack of time series for ice cover parameters since the mid-1980s may be filled successfully by using microwave satellite observations that provide reliable, regular and weather-independent data on ice cover.

In our study, we use the synergy of two types of satellite observations: (i) passive microwave data from SSMR and SSM/I sensors (since 1978) as well as (ii) a combination of simultaneous data from active (radar altimeter) and passive (radiometer) microwave instruments onboard the TOPEX/Poseidon satellite (since 1992).

An assessment of ice conditions from historical observations is given to provide a background to compare with satellite-derived data. The ice algorithms were applied for satellite data; series of dates of first and last observation of ice cover, duration of ice season as well as ice extent area have been computed for various regions of the Caspian and Aral Seas. These time series show pronounced regional, seasonal and interannual variability. There is a marked decrease of both duration of ice season and ice extent since the winter 1993/1994. Several factors that may explain this warming signal are discussed, as well as existing and potential implications of changes in ice conditions for industrial activity and the sea ecosystems.

Keywords: Ice cover; Caspian Sea; Aral Sea; Microwave radiometers; Satellite altimetry

1. Introduction

Every winter, the Caspian and Aral Seas are covered by ice. The presence of ice negatively affects navigation, fisheries and other industrial activities. Of special

* Corresponding author. Centre d'Etudes Spatiales de la Biosphère (CESBIO), BPI 2801, 18, Ave. E. Belin, 31401 Toulouse CEDEX 4, France. Fax: +33-5-61-55-85-00.
E-mail address: kouraev@cesbio.cnes.fr (A.V. Kouraev).

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doi:10.1016/j.jmarsys.2003.12.011

Fig. 1. Ice-breaker "Captain Bukaev" leads a caravan of ships from Astrakhan to the Caspian Sea (photo by P.I. Buharizin).

concern is the impact of sea ice on industrial structures located in the coastal zone, such as Russian and Kazakh oil prospecting rigs operating on the Northern Caspian shelf. Ice conditions make it necessary to maintain an ice-breaker fleet (Fig. 1) as well as to use oil drilling rigs of arctic-class in the Northern Caspian.

Ice processes in these seas have a significant temporal and spatial variability, influenced by meteorological conditions, wind fields and water currents, as well as by sea morphology. Both seas are located on the far southern boundary of sea ice cover development in the Northern Hemisphere. Due to this marginal location, data on ice variability in these seas may serve as an early indicator of large-scale climate change. However, as will be shown in Section 2, publicly available information on ice conditions in these seas after the mid-1980s is absent. Our aim is to fill this information gap and analyse recent variability of ice cover using passive and active satellite microwave data from 1978 to the present.

2. History of studies of ice conditions

Studies of sea ice in the Caspian Sea have began in the second part of the XIX century, when observations were carried out at coastal stations. Since 1927, these observations were complemented by aerial surveys (Table 1) that initially were not regular and provided information mostly for operational needs of navigation and fisheries. During World War II, the observations became much more complex and frequent. Later on ice studies became part of the national hydrometeorological monitoring system and were performed on a regular basis. Since the late 1970s, the high cost of aerial surveys led to a dramatic decrease of aerial ice cover observations. The lack of information was partially compensated for by the use of satellite imagery, mainly in the visible and infrared range (Krasnozhon and Lyubomirova, 1987; Buharizin et al., 1992), but due to frequent cloud cover in the winter this source was used only occasionally. The majority of satellite-based ice maps were made in the 1980s, using data from low-resolution Soviet weather satellites such as "Meteor".

In the Aral Sea, regular ice observations at coastal stations began in 1941 and by means of aerial surveys in 1950. They were done on a regular basis and, up to 1985, 241 aerial surveys were carried out (Bortnik and Chistyayeva, 1990). As was the case for the Caspian Sea, since the late 1970s, the frequency and number of aerial surveys in the Aral Sea sharply decreased, due to financial problems as well as to general degradation of the sea related to rapid sea level fall.

Table 1
Number of ice charts based on aerial surveys and satellite data for the Northern Caspian Sea from 1927 to 2002 (based on the data from Terziev et al., 1992; Buharizin and Sharomov, 2002)

Period	Number of winters	October	November	December	January	February	March	April	Total
Aerial surveys									
1927–1930	3	0	1	5	3	5	5	0	19
1930–1934	4	0	0	0	0	0	0	0	0
1934–1941	8	0	5	14	19	32	32	1	103
1941–1945	4	0	34	39	41	46	31	19	210
1945–1960	15	9	69	82	78	96	93	30	457
1960–1979	19	2	23	74	81	112	81	17	390
1979–1988	9	1	4	10	14	23	24	4	80
1988–1993	5	0	0	1	6	5	12	1	25
1993–2002	9	0	0	0	0	4	2	0	6
Total	76	12	136	225	242	323	280	72	1290
Satellite data									
1979–1988	9	1	4	23	48	54	62	10	202
1988–2002	17	0	0	9	24	31	13	3	80
Total	26	1	4	32	72	85	75	13	282

As a result, all published continuous time series of various ice cover parameters for the Caspian and Aral Seas stopped in 1984–1985. The results of observations for later periods are less regular and still reside in local archives.

3. Ice conditions from historical records

In order to assess the variability of ice conditions of the Caspian and Aral Seas and to provide a background to compare with satellite-derived data, an overview of historical assessments of ice conditions (Kosarev, 1975; Bortnik and Chistyayeva, 1990; Terziev et al., 1992; Kosarev and Yablonskaya, 1994) is given here. Most of the existing sources of information on the ice condition in the Caspian and Aral Seas are published in the Russian language and thus remain inaccessible for many western readers. It is also worth noting that these publications refer to the data on ice cover mainly up to the mid-1980s.

3.1. Ice conditions in the Caspian Sea

Traditionally, the Caspian Sea is divided into three parts—the deep Southern and Middle Caspian, and shallow Northern Caspian. Ice cover may form in all three parts of the sea. However, in the southern part, it appears only in extreme severe winters and in the middle part ice cover occupies small areas near the coast, while during mild winters it does not appear at all. Only in the Northern Caspian is ice present every year and covers large areas. In this part of the sea, the presence of significant areas with shallow depths (less than 10 m) results in an intensive interaction of ice cover with the sea bottom and rapid changes in sea level during storm surges.

Ice conditions in the Northern Caspian strongly depend on the thermal type of winter (Fig. 2). During moderate winter conditions, ice formation starts in mid-November in the very shallow northeastern regions. Then, it gradually spreads out to the west, reaching regions near the Volga delta at the end of November. In December, ice cover is present on all areas of the Northern Caspian with depths less than 5 m. Further development of ice cover is limited by larger depths and increased water exchange with the Middle Caspian; only in January does ice appear in the regions with depths from 7 to 10 m. In mild winters, ice formation starts 10–20 days or more later, while in severe winters it starts 20–30 days earlier.

Quite often (in mild and moderate winters) young ice melts away with the first thaw and then forms again; this process can be repeated many times. However, in severe winters, ice becomes stable in just a few days and remains until spring. Winds in this region are very

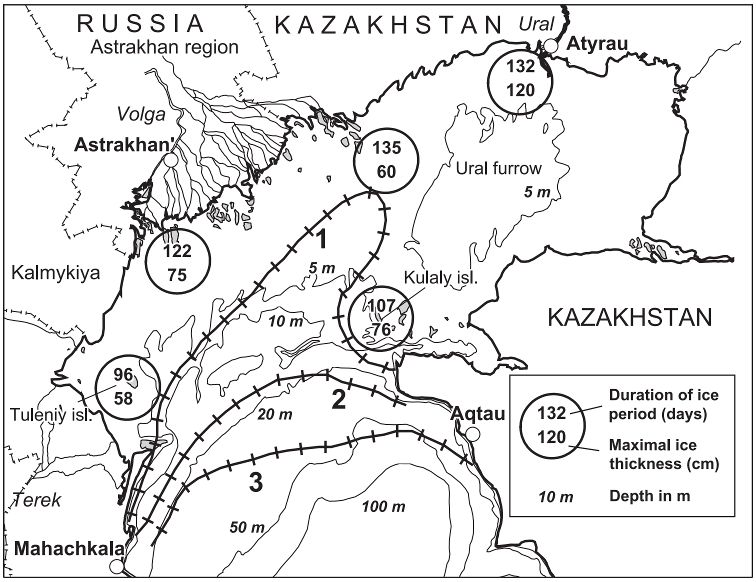

Fig. 2. Ice conditions in the Northern Caspian: boundaries of drifting ice in mild (1), moderate (2) and severe (3) winters, average duration of ice period (days) and maximal ice thickness (cm) (after Atlas, 1997).

strong and their influence results in intensive deformation of the ice cover and subsequent cracking, fracturing, rafting, as well as the formation of hummocks and ridges. Some hummocks become anchored on the ground, reaching 2–4 m (in some cases, 6 m) height (Terziev et al., 1992).

The thickest pack ice is observed in the eastern part of the North Caspian in January, averaging 40–50 cm, while in the region of the Volga delta it is observed in February (20–30 cm). In severe winters, ice thickness may increase up to 75 cm in the western and central regions and 120 cm in the eastern parts (see Fig. 2).

Ice decay starts in March: open areas and shallow regions in the northwestern part become ice-free in mid-March and in the region near the Volga delta by late March. In the beginning of April, the ice disappears in the northeastern part; the last ice resides over the Ural furrow. On average, the duration of the ice period is 120–140 days in the eastern part of the Northern Caspian and 80–90 days or less in the western part.

3.2. Ice conditions in the Aral Sea

The sea level decrease of the Aral Sea that started in the mid-1960s led to significant changes in the sea shape and depth and, as a result, in many oceanographical parameters, such as the heat storage, water salinity, water exchange and circulation, etc. From 1960 to 1987, the sea level decreased by 13 m and the sea surface by 40%. Since 1988, the Small (northern part) and Large (southern part) Aral became completely divided, actually forming two separate seas. Historical assessment of the ice cover parameters discussed in this section are still based on observations made when the Aral Sea was one water body.

The ice conditions are the most severe in the northern and eastern parts of the sea. The ice formation usually begins in the northern and northeastern coastal regions in mid-November, in the south by the end of November, in the open sea by end of December, while in the western coastal zone ice forms only in the beginning of January. Variability of the dates of ice formation onset varies from 1 to 2 months depending on the region.

In moderate winters, by mid-December, the pack ice is 20–30 km wide along the northern and northeastern coast. In January, it covers the whole Small Aral Sea and regions along the eastern and southern coasts. As well it appears on the western coasts (bands of 4–6 km width). The maximal development of ice cover is in February, when, in severe winters, ice may cover the whole sea surface. The greatest ice thickness, observed in February (sometimes in March), reaches 65–70 cm in the northern and 35–45 cm in the southern parts. As in the Northern Caspian, the distribution of drifting ice in the open Aral Sea is influenced by the wind field conditions, and the northeasterly and easterly winds often lead to rapid increase in ice concentration in the southern part of the sea.

Ice decay starts in the second half of February or the first half of March. Usually, the southern and southeastern parts become ice-free at the end of March and the northern coast in mid-April. However, in severe winters, ice may reside until the end of April or beginning of May. The number of days with ice ranges from 120–140 days in the north to 100–110 in the south, while in the western regions it is minimal—70–80 days.

4. Data and methods

The efficient planning of ship routing, fisheries and other industrial activity requires a comprehensive and up-to-date assessment of ice conditions in the Caspian and Aral Seas. Furthermore, data on recent variability of ice cover are useful for climate studies as well as forcing and verification of general circulation models. However, the current lack of time series for ice cover parameters since the mid-1980s may be successfully filled by using microwave satellite observations that provide reliable, regular and weather-independent data on ice cover. In our study, we use two types of microwave satellite data.

4.1. Passive microwave data from SMMR and SSM/I

A first source of satellite data is a more than 20-year long passive microwave data set from Scanning Multichannel Microwave Radiometer (SMMR, 1979–1987) instrument onboard the satellite NIMBUS-7 and from the Special Sensor Microwave/Imager (SSM/I) instrument onboard the Defense Meteorological Satellite Program (DMSP) series (since 1987). These radiometers with incidence angle from 50.2° to 52.8° provide measurements of brightness temperature at different frequencies and at different (vertical or horizontal) polarisations.

The National Snow and Ice Data Center (NSIDC) provided the SMMR and SSMI data mapped to the Equal Area (625-km^2 resolution) SSM/I Earth Grid (EASE-Grid) projection. To minimise the effects of ice and snow melt, only night brightness temperatures were used (thus affecting the choice of ascending or descending passes). The initial data were averaged to obtain pentad (5 days) mean values in order to get continuous spatial coverage.

There are several approaches for estimating ice cover concentration using passive microwave data (Steffen et al., 1992; Comiso, 1986; Swift and Cavalieri, 1985). Most of these algorithms use brightness temperature (TB) data from the 19.35 (18.0 for SMMR) and 37.0 GHz horizontally (H) and vertically (V) polarised channels. These data are used to calculate the polarisation (PR) and spectral (GR) gradient ratios, defined by:

$$\mathrm{PR} = \frac{\mathrm{TB19V} - \mathrm{TB19H}}{\mathrm{TB19V} + \mathrm{TB19H}}$$

$$\mathrm{GR} = \frac{\mathrm{TB37V} - \mathrm{TB19H}}{\mathrm{TB37V} + \mathrm{TB19H}}$$

Most existing sea ice algorithms (such as the NASA Team or Bootstrap algorithms) were developed for Arctic or Antarctic conditions and they need to be adjusted and validated before being applied to the Caspian and Aral Seas. Currently, we apply a simplified algorithm that uses PR and GR ratios with a threshold (defined as a linear relationship between PR and GR) in order to distinguish between ice and open water. After validation by in situ data and information from other satellites, this algorithm will be further developed to provide ice concentrations in these seas.

4.2. Satellite altimetry data

The other source is the data from the TOPEX/Poseidon (T/P) satellite, operating since 1992. This platform has two nadir-looking instruments—a dual-frequency radar altimeter and a microwave radiometer used to correct altimetric measurements for atmospheric influence. Until now, there were very few initiatives to use the synergy of the simultaneous observations from active and passive microwave instruments. However, such a combination looks very promising for the studies of snow covered regions using data from T/P and the SSM/I radiometer satellite (Papa et al., 2002) as well as for analysis of ice cover parameters (Kouraev et al., 2003a,b). We consider the T/P observations in the space of (i) backscatter coefficient (called σ_0) at 13.6 GHz, which is the ratio between the power reflected from the surface and the incident power emitted by the onboard radar altimeter, versus (ii) the average value of temperature brightness at 18 and 37 GHz, to discriminate between open water and ice using a set of threshold values (Kouraev et al., 2003a). The satellite flies over the same location every 10 days; use of the 1-Hz data provides an along-track ground resolution of about 6 km.

4.3. Data selection

In order to ensure that the satellite observations do not cover land regions (that would otherwise contaminate the measurements), a geographical selection of data was done (Figs. 3 and 4). T/P data closer than 20 km from the coast and EASE-grid pixels covering coastal regions or islands were not used. For the Northern Caspian Sea, two sub-regions were identified, the western and eastern parts. For the Aral Sea, in order to account for the variability of the sea level, SMMR

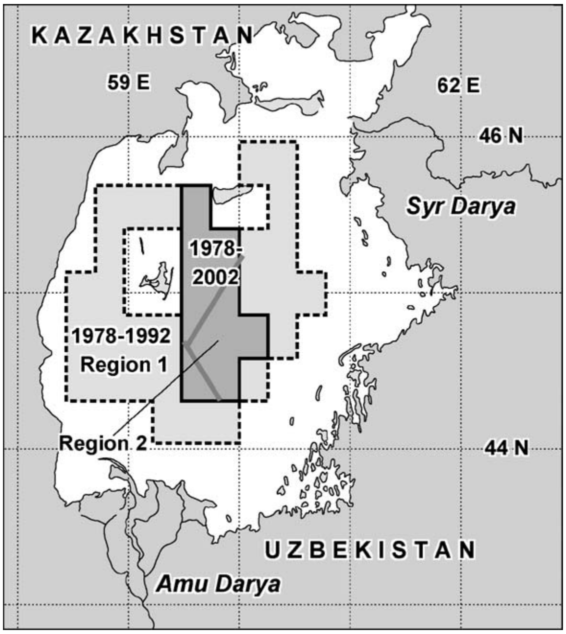

Fig. 4. Parts of TOPEX/Poseidon ground tracks over the Aral Sea (grey lines) and EASE-grid pixels for regions 1 and 2.

Fig. 3. Parts of TOPEX/Poseidon ground tracks over the Northern Caspian (grey lines) and EASE-grid pixels used for western and eastern parts.

and SSM/I data were selected for two regions, a larger one region 1 (delimited by the coastline location in 1992) and a much smaller region 2 that corresponds to the most recently available coastline locations in 2002 (see Fig. 4). Data for region 1 may be used for 1978–1992 (and, with less reliability, even after 1992), while data from region 2 provide heterogeneous series of ice conditions in the central part of the Aral Sea for the whole period of satellite observations.

5. Results

The described methods were applied to the satellite data and various ice cover parameters were computed. The ice cover extent derived from T/P data for each ground track and for each 10-day period was calculated as the ratio (%) of observations classified as ice to the total number of observations. For SMMR or SSM/I data, the ice extent was calculated as number of pixels classified as ice. For some pentads, the data were not available; in this case, the ice extent was interpolated using data for neighbouring pentads. In order to assess the conditions for each winter, we used two parameters—(i) maximal area of ice development (in km^2), which corresponds to the method used for historical observations, and (ii) the total number of ice pixels for each winter. The second parameter is more robust in estimating the degree of severity of winter, as it avoids ambiguity in cases when one short and one long winter have the same area of maximal ice development. These would be considered as equally severe when using only maximal area, which is not true.

By averaging these data in time and space, dates of first and last observation of ice cover, duration of ice season (Figs. 5–7) and ice extent (Figs. 8 and 9) have been computed for various regions of the Caspian and Aral Seas. These time series show pronounced regional, seasonal and interannual variability.

5.1. Ice duration

The dates of the first and last observed ice, as well as the duration of the ice season (excluding days where there was no ice observed) determined from passive microwave sensors (SMMR and SSM/I) as well as from T/P satellite were analysed for the western and eastern part of the Northern Caspian and for the central part (region 2) of the Aral Sea.

The start of the ice season is observed differently by passive microwave sensors and TOPEX/Poseidon. SMMR and SSM/I brightness temperatures are known to be poorly sensitive to new thin ice. At the same time, the presence of an active microwave instrument

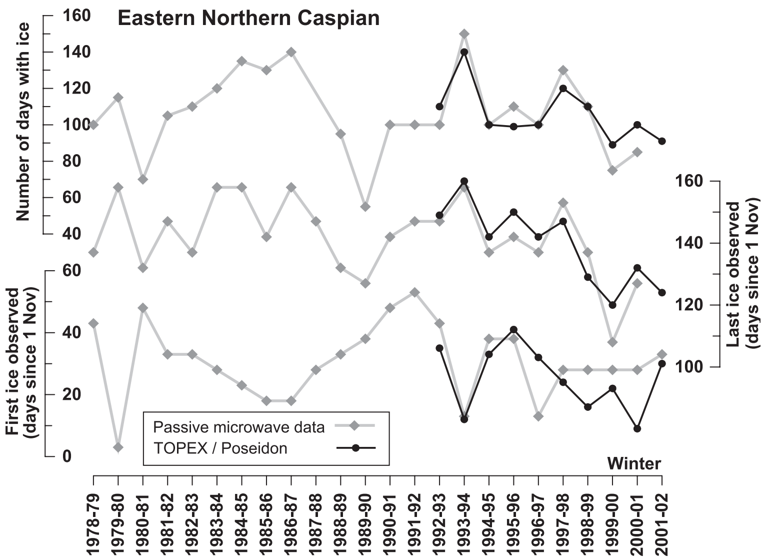

Fig. 5. Eastern Northern Caspian: satellite-derived dates of the first and last observed ice and duration of ice season (number of days with ice observed).

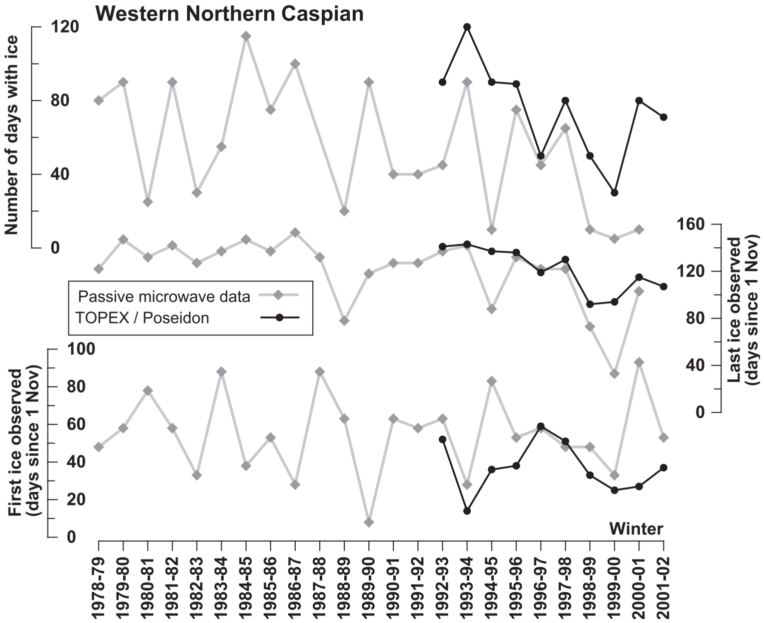

Fig. 6. Western Northern Caspian: satellite-derived dates of the first and last observed ice and duration of ice season (number of days with ice observed).

onboard the T/P allows one to identify, more easily, new ice and small ice floes, as well as rotten ice. This results in a tendency for T/P to identify the beginning of the ice season earlier and the end of ice season later than SMMR and SSM/I. As a result, the duration of the ice season is found to be longer in some winters

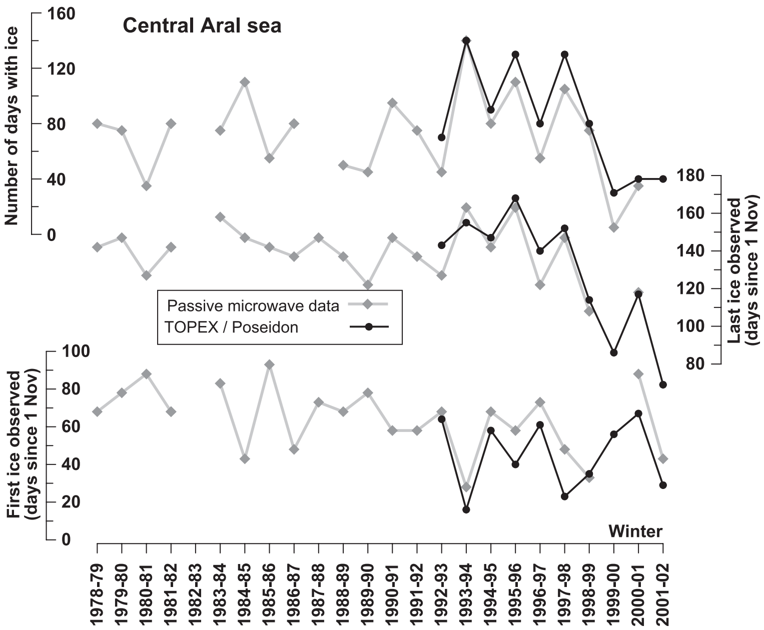

Fig. 7. Aral Sea (region 2): satellite-derived dates of the first and last observed ice and duration of ice season (number of days with ice observed).

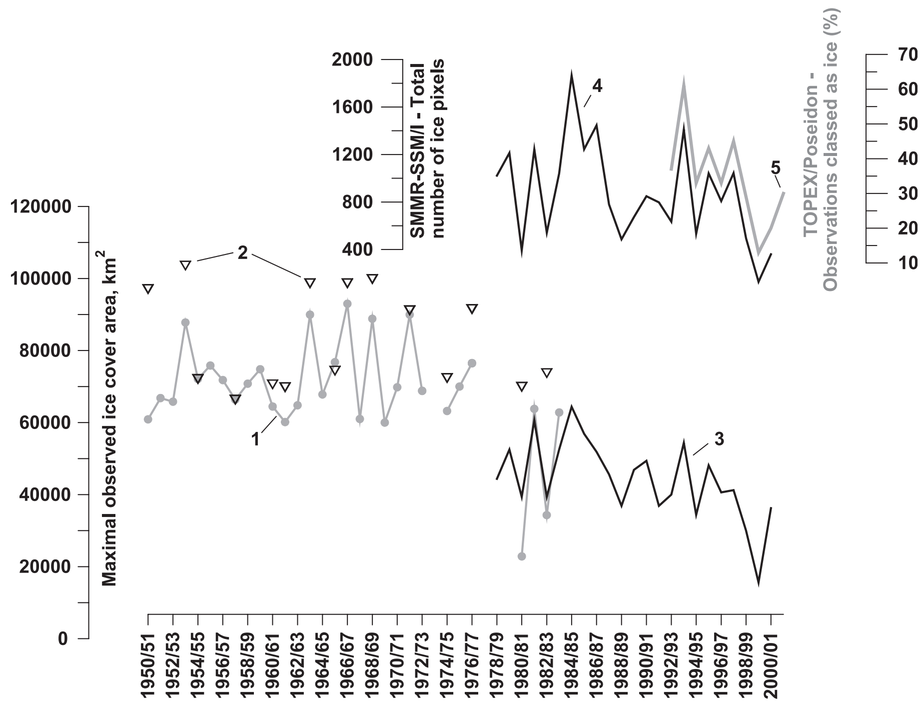

Fig. 8. Ice conditions in the Caspian Sea. Historical observations (using data from Terziev et al., 1992): (1) maximal area of pack ice and (2, triangles) total (pack+drifting) ice. SMMR and SSM/I data: (3) maximal area of ice cover and (4) total number of pixels classified as ice for each winter. TOPEX/Poseidon data: (5) average ratio (%) of observations classified as ice for each winter.

with the altimetry data than with the radiometer data (such as for the western part of the Northern Caspian, where the difference in estimated duration of the ice season amounts, in some winters, up to 60–70 days).

In the Northern Caspian, the beginning of the ice season does not reveal discernible trends. In the eastern part, the ice season starts from mid- to late-November to mid-December, depending upon climatic conditions. The western part is more affected by water exchange with the Middle Caspian and by Volga runoff, thus the ice season begins later here and these dates vary more than in the eastern part—from mid-November to the end of January. These dates correspond well with the historical observations.

The dates of the end of the ice season since the mid-1990s show a tendency for winters to end earlier than before. In the western part of the Northern Caspian, there is a slight decrease of dates: before the mid-1990s the timing of the end of the ice season ranged from the end of January to the end of March, while after that the latest observed dates were at the beginning of March. In the eastern part, this tendency is more pronounced—before 1995, the winters usually ended in the beginning of March beginning of April; after 1995, the earliest dates shifted towards the end of February.

The duration of the ice season in the eastern part is relatively stable, ranging from 70 to 145 days, with typical values around 100–110 days. This also corresponds to historical observations. In the western part, the duration varies from 20 to 120 days, with a recent (since mid-1990s) decreasing trend observed both by SSM/I and T/P.

In the central part of the Aral Sea, for the period of satellite observations, there is a trend for winter to start earlier—from the beginning of December end of January this range has changed to mid-November mid-January. Even more marked is a tendency for winter to end earlier—from end of February end of March to end of January—end of February, a difference of one month. The maximal duration of the ice season increased slightly from 90 to 100–120 days in the mid-1990s; however, the minimal durations dropped from

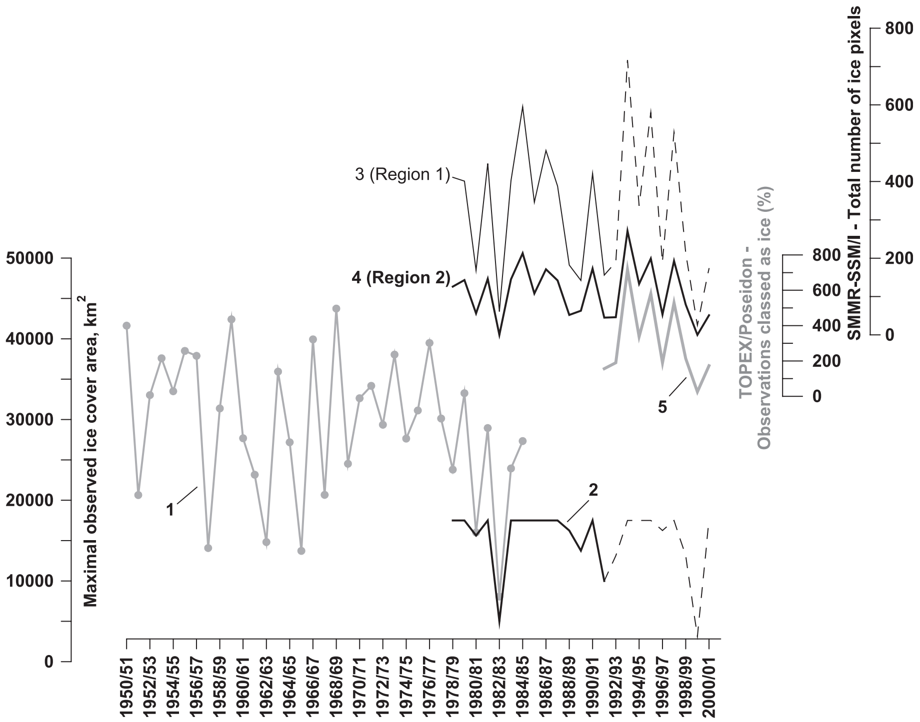

Fig. 9. Ice conditions in the Aral Sea. Historical observations (recalculated from Bortnik and Chistyaeva 1990) of (1) ice cover development in km^2. SMMR and SSM/I data: (2) maximal area of ice cover development for large region 1, total number of pixels classified as ice for each winter for region 1 (3) and in the smaller region 2 (4). For region 1 data after 1992 contain pixels with observations affected by recently exposed land areas. However, though they are less reliable, they are still plotted (dotted line) in order to show the minimal values of ice cover development in mild winters. TOPEX/Poseidon data: (5) average ratio (%) of observations classified as ice for each winter.

40 days to 10–30, especially evident during the last 3–4 winters.

All these observations indicate changes in ice conditions that are taking place recently, starting in 1992–1994. As will be shown later, these changes are also reflected in the data on ice extent.

5.2. Ice extent

The historical observations of maximal ice cover development are heterogeneous—up to the end of the 1970s these estimates were based on regular aerial surveys, while in the 1980s the number of surveys decreased and, thus, the maximal ice extent values became smaller and less reliable. Available values between 1980 and 1985 vary from 20 000 to 60 000 km^2, while they were in the range from 60 000 to 95 000 km^2 before. For the Aral Sea, the historical data are more homogeneous. They were initially provided (Bortnik and Chistyayeva, 1990) as % of sea surface, but we recalculated them as km^2 using the mean annual values of sea surface for each year.

The comparison of historical and satellite-derived data is complicated by several factors. First of all, the chosen EASE-grid pixels do not cover the coastal areas and thus the maximal possible values will always be less than the data from aerial surveys (especially for the Aral Sea). Second, the algorithm currently used does not distinguish between pack and drifting ice, which creates problems for comparison with data for the Caspian Sea. However, both historical and satellite-derived observations show high interannual variability with many similar features during the overlap period. In the Aral Sea estimates of the maximal ice extent during the mild winters of 1980/1981 and 1982/1983 are very close, even in absolute values. Both seas are characterised by a “seesaw-like” variability of ice conditions; milder and severe winter conditions alternate with 2–3-year intervals. This variability is often superimposed on warming or cooling trends of larger scale (such as in the case of the Aral Sea from 1945 to 1983).

The comparison of the total number of ice pixels from SMMR and SSM/I with the TOPEX/Poseidon observations shows that, in spite of various units of measurements and different spatial coverage, both series agrees very well. Both types of data indicate a recent continuous decrease of ice extent in the Caspian and Aral Seas since the winter 1993/1994–especially in 1999/2000, when the values reached the lowest mark for the whole period of satellite observations. This period of decreasing ice extent is also marked by changes in the dates of start and end of the ice season and its total duration.

6. Discussion

The observed warming signals in the Caspian and Aral Seas may come from several factors. For the Aral Sea, this may be partly explained by the continuing decrease of sea volume (and thus of heat storage capacity) and the increase of salinity, that from 1995 to 2001 increased in the central part of the Aral Sea from 42 to 155–166 ppt (Mirabdullayev et al., 2003). This increase of salinity would have shifted the freezing temperature (without account of the particularities of salt composition of the Aral Sea) from −2.27 to −8.96 °C, using the formula $T_{fr}=-0.054*S$ from Zubov (1945), where T_{fr} is the freezing temperature and S is the salinity in ppt. The decrease of heat storage capacity would result in an earlier start of ice formation in autumn and an earlier ice break-up and melting in the spring, while the increase of salinity would lead to a general decrease of ice season duration and ice extent. All these features were observed using the satellite data for the Aral Sea.

However, the change in dates of beginning and end of the ice season and the decrease of ice extent are also evident in the Caspian Sea, where no significant changes in heat storage capacity and water salinity are observed. This indicates changes in the thermal regime resulting in abnormally mild recent winters in both the Caspian and Aral Seas. Is this indicative of a long-term warming trend or just a series of mild winters?

To answer this question, we need to analyse further the variability of the ice cover as a function of climatic parameters and to extend the time series with new types of data. While the hypothesis of a warming trend is still under consideration, several possible consequences are already visible. Reduction of ice cover in 1998–2002 severely affected living conditions of the unique mammal in the sea, the Caspian seal, listed as vulnerable on the IUCN Red List of Threatened Species. From January to April, seals gather on the sea ice in the Northern Caspian Sea, when they pup, nurse, mate and molt. The lack of stable ice cover brought degraded conditions for seal breeding. The resulting weakening of their immune system is aggravated by the spreading of viruses and may lead to cases of mass mortality, as in 2000 when canine distemper virus affected a large part of the seal population; between 20 000 and 30 000 seals were found dead.

The potential climatic warming and the consequent reduction of ice cover may have beneficial consequences for navigation and fisheries. However, it also may result in changes of many environmental parameters, for example, increasing the probability of extreme meteorological conditions, such as strong winds and storms. This will negatively affect operating conditions for various industrial activities. A recent example is a situation in the Northern Caspian (February 2002), when the influence of western winds blowing with hurricane force resulted in the compaction of ice cover in the eastern part of the sea, appearance of large areas of hummocking, and increase of sea level (Buharizin, in press). At that time, an accident was barely avoided at the Kazakh oil rig "Sunkar". In order to protect it from drifting ice, four specially designed barges ("ice barrier") were submerged around the oil rig. Under such severe ice conditions, one of the barges started to drift away and was dragged by drifting ice for 120 m along the sea bottom. Fortunately, the oil rig was not in its path and was not damaged.

7. Conclusions and perspectives

The synergy of simultaneous data from nadir-looking active and passive sensors onboard the TOPEX/Poseidon satellite and passive microwave observations from SMMR and SSM/I represent a significant potential for the studies of sea ice cover and, for the first time, provide us with a continuous series of ice cover parameters for the Caspian and Aral Seas since the mid-1980s. Further validation and improvement of the ice algorithms using in situ and other types of satellite data will provide additional information on ice concentration, ice roughness and other parameters. Comparison of ice conditions parameters in the Caspian and Aral Seas with external climatic data will improve our understanding of the natural processes in these seas.

The combination of the specific advantages of both types of observations—wide spatial coverage and temporal resolution of SMMR-SSM/I and high radiometric sensitivity and along-track spatial resolution of TOPEX/Poseidon—will significantly enhance the capabilities of microwave measurement for future ice studies. Their use will bring substantial benefits for the monitoring and management of the marine environment.

Acknowledgements

The research was supported by the French Ministry of Research through a post-doctoral fellowship for Alexei Kouraev in 2001/2002, by the AICSEX (Arctic Ice Cover Simulation Experiment) Project of the 5th EU Framework program and by the INTAS Project 00-1053.

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