Ice cover variability in the Caspian and Aral seas from active and passive microwave satellite data

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The paper discusses time and space variations of ice extent in the Caspian and Aral seas during the last decade (1992–2002). It uses synergy of data from active (radar altimeter) and passive (radiometer) microwave nadir-looking instruments onboard the TOPEX/Poseidon satellite. The proposed approach is substantiated and validated using both in situ and satellite imagery data for the Caspian Sea. The results indicate significant spatial and temporal variability of ice conditions, with a significant decrease of both the duration of ice season and ice extent during the last four winters (1998–2002). The TOPEX/Poseidon-derived time series of sea ice extent are very valuable in view of the fragmentary and mostly unpublished data on ice conditions on the Caspian and Aral seas since the mid-1980s.

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A stable and strong ice cover forms during winter months in the Aral Sea and northern part of the Caspian Sea. The presence of ice cover negatively affects navigation and fishery conditions and endangers facilities located on the coast as well as on the shelf, such as oil rigs that have recently been installed in the northern Caspian by Russia and Kazakhstan. Ice conditions in these two seas vary significantly from year to year in response to meteorological changes. Data on ice cover variability may therefore serve as an early indicator of large-scale climate change (Allison et al. 2001).

Regular studies of ice cover in the Caspian and Aral seas started in the first half of the 20th century (Bortnik & Chistyayeva 1990; Terziev et al. 1992). With the collapse of the Soviet Union, data on ice conditions for these seas became very scarce. Most published time series of ice cover parameters stop in the mid-1980s. For the past decade, data that reside in local archives are irregular, exist in heterogeneous forms (data from aerial surveys and field research, satellite imagery, etc.), are stored on different media, and are not available to the public. For the region of the northern Caspian Sea and lower Volga there are some recent initiatives to compile these data into a comprehensive atlas of ice features (Buharizin & Sharomov 2002) but this work is just in the beginning stage.

For many years, global sea ice cover has been studied using satellite observations, especially from instruments operating in the microwave range, such as passive radiometers, SAR, radar altimeters, etc. (Allison et al. 2001). Numerous studies of ice cover variability have been conducted using passive microwave observations

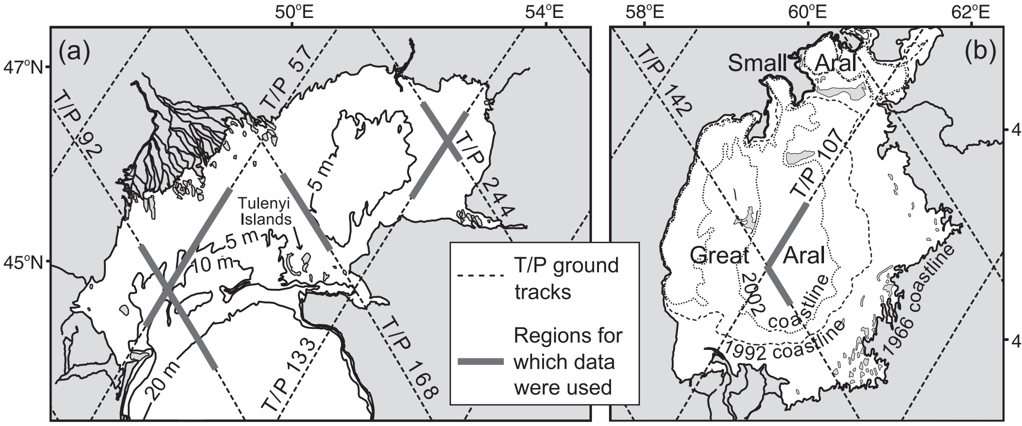


Fig. 1. TOPEX/Poseidon (T/P) ground tracks over (a) the northern Caspian and (b) Aral seas, and regions for which data was used. The Aral Sea's 1966, 1992 and 2002 coastlines are indicated in (b).

from SMMR and SSM/I instruments (Zwally et al. 2002), providing global observations of ice extent with high temporal resolution (five-day complete coverage). For the Caspian and Aral seas, satellite information has been used since the late 1970s. Radar altimeter data from TOPEX/Poseidon were successfully used to assess variations of the Caspian sea level (Cazenave et al. 1997). However, studies of ice cover have been based mostly on data in the visible and infrared range (Krasnozhon & Lyubomirova 1987; Buharizin et al. 1992). Due to the frequent presence of winter cloud cover over these seas, this information is fragmentary and has not been routinely used.

It is nevertheless crucial to continue data acquisition in order to construct long time series of ice extent and ice season duration and to provide information for various purposes—from practical applications relating to ship routing and protection of industrial facilities to studies of ice variability and change, as well as forcing and verification of general circulation models (Rayner et al. 2002).

The time series of ice season duration and ice presence that are discussed in this paper are based on altimetry and radiometry data from the TOPEX/Poseidon satellite. They show evidence of recent changes in ice conditions over the Caspian and Aral seas during the last decade. This is probably the first attempt to fill this important information gap.

Ice processes in the Caspian and Aral seas have significant temporal and spatial variability, influenced by factors such as air temperature, sea depth, wind fields and water currents, as well as sea level changes (Kosarev 1975; Bortnik & Chistyayeva 1990; Terziev et al. 1992; Kosarev & Yablonskaya 1994). Significant areas with shallow depths (less than 10 m) favour intensive interaction between ice cover and the sea bottom as well as rapid changes in sea surface and the location of the coastline with variations in sea level.

The Caspian and Aral seas are known to have undergone dramatic sea level changes during the last century (Bortnik & Chistyayeva 1990; Kosarev & Yablonskaya 1994; Cazenave et al. 1997). Between the early 1920s and late 1970s, the level of the Caspian Sea fell; by 1977 the level had decreased by 3 m, reaching the lowest mark in the last 400 years. After that point, and quite unexpectedly, the Caspian sea level rapidly began to rise by more than 2 m until 1995, when it started slowly to decrease again.

The Aral sea level was relatively stable until the early 1960s, when consumption of Syr Darya and Amu Darya river waters for agricultural purposes finally exceeded the incoming part of the water budget. Between 1960 and 1987, sea level dropped by 13 m and the sea surface area decreased by 40%. Since 1988 the sea has been divided into two separate basins: the Small Aral in the north and the Great Aral in the south, connected by a small channel. Since 1992 several attempts to build a dam between the Small and Great Aral have been undertaken with the purpose of refilling the Small Aral with water (Stone 1999). This has resulted in differing variability of sea level in those two basins (Mercier 2001). Changes in sea level greatly influence ice conditions through changes in the heat storage capacity, water exchange and circulation (Bortnik & Chistyayeva 1990; Terziev et al. 1992).

Data and methods

We have studied the ice cover in the Caspian and Aral seas using active and passive microwave data from the TOPEX/Poseidon (T/P) satellite, launched in 1992. T/P has two main nadir-looking instruments: a dual-frequency radar altimeter (5 and 13.6 GHz, C and Ku bands, footprint diameter 12.8 km in Ku band) and a passive microwave radiometer operating at 18, 23 and 37 GHz (footprint diameter 42, 35 and 22 km, respectively). Until now, there have been very few initiatives to exploit the synergy of simultaneous observations from active and passive microwave instruments. However, such a combination looks very promising for 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. 2002a; 2002b).

The data we analysed consist of the merged T/P products (GDR-Ms), provided by the Archiving Validation and Interpretation of Satellite Data in Oceanography Data Centre of the Centre National d'Etudes Spatiales, for orbital cycles from 1 to 351 (September 1992 to April 2002). The satellite tracks cover the world between 66° N and 66° S, and overfly the same location every 10 days. We use the 1 Hz data, which provide an along-track ground resolution of about 6 km.

Five T/P ground tracks cover the northern part of the Caspian Sea, where ice cover is present during each winter (Fig. 1a). Two ground tracks over the Aral Sea were selected (Fig. 1b).

For the altimetry information, we use the 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. Over ocean surfaces, σ_0 is typically on the order of 10 - 12 dB (Fu & Cazenave 2001), while on sea ice this value is much larger, in the range 30 - 40 dB. Use of the backscatter coefficient allows us to characterize the reflecting properties of the surface. For the radiometry information, we use temperature brightness at 18 and 37 GHz. Ice surface has much higher temperature brightness values than water surface (Ulaby et al. 1986), which permits discriminating between water and ice.

In our work we use a combination of active and passive microwave data, analysing time series of T/P observations and their distribution in the space of (i) backscatter coefficient at 13.6 GHz versus (ii) the average value between temperature brightness values at 18 and 37 GHz (Fig. 2a). It is readily seen that in some cases discrimination between ice and water using only radiometer (for example, when the average value between brightness temperatures is between 170 and 210 °K) or only altimeter data would be difficult due to arising ambiguities. But the synergetic approach proposed here allows the easy discrimination of open water and ice as two distinctive groups of observations. These groups reside in the lower left (open water) and upper right (sea ice) corners of Fig. 2a. Moreover, study of temporal variations confirms that observations in the upper right corner are typical only for winter months, with number of observations increasing with the development of ice cover and decreasing with ice melting (Fig. 2b).

The combined T/P data provide information for ten consecutive winters (1992/93 to 2001/02) with a 10-day repetitive period. We used data for winter months (from November to April). Data closer than 20 km from the coast were excluded to ensure that observations do not cover land regions, which would contaminate the radiometer measurements. For the Aral Sea the data were selected using the coastline location at the lowest sea level mark (in 2002), calculated using our dedicated high resolution digital bathymetry model. Data from individual T/P ground tracks have various geographic locations along the tracks, so to account for spatial dispersion of the repetitive tracks, 0.05 degree latitude bins were considered for each pass and data were referred to the coordinates of the centre of the nearest bin.

The results presented here show that the combination of data from active and passive microwave sensors provides enough information to discriminate between open water and ice. Moreover, study of the temporal variability of the distribution of observations suggests that various stages of ice cover development correspond to specific areas in the backscatter / brightness temperature space, thus reflecting changes in the reflecting properties of ice cover (Fig. 2a).

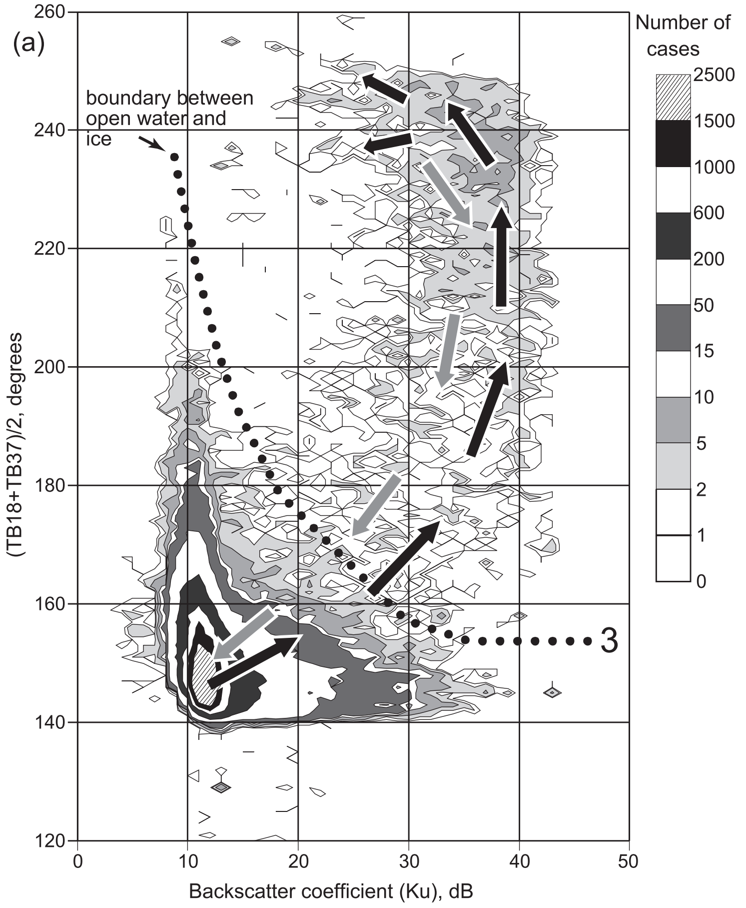


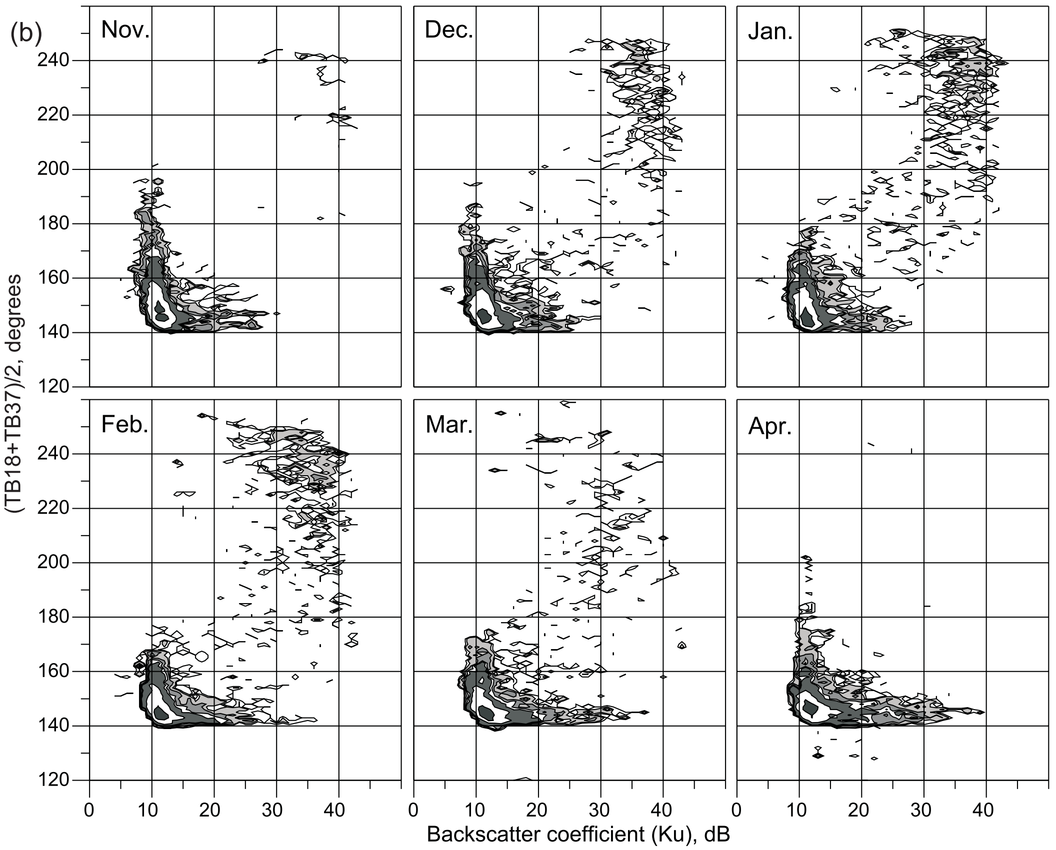
Fig. 2. (a) Annual and (b, opposite page) monthly distribution of observations for TOPEX/Poseidon cycles 1 through 330 for the northern Caspian Sea in the space of (i) backscatter coefficient at 13.6 GHz versus (ii) the average value of temperature brightness at 18 and 37 GHz. Calculation was done segmenting the space with a resolution of 1 dB on the X axis and 1 °K on the Y axis. Arrows show typical evolution of distribution of observations with (black arrows) ice development and (grey arrows) decay. The dotted line in (a) indicates the boundary between open water and ice. Similar distribution was found for the Aral Sea.

Validation of method

Lack of in situ observations of ice cover in the Caspian and Aral seas during the T/P time span poses problems for large-scale validation of the proposed method. However, we were able to assess its applicability using independent in situ and other satellite data over the Caspian sea in November–December 2001. In situ observations of sea ice cover (Buharizin in press) were made on the ships *Khongay* and *Nord*, operating in the northern Caspian. *Nord* was in the vicinity of the Kazakh oil rig known as *Sunkar*. Designed for the harsh environmental conditions of the northern Caspian, *Sunkar* is the largest Arctic-class barge drilling rig in the world (Rigzone 2001). Analysis of the spatial distribution of ice cover is further extended using satellite image of 3 December 2001 from MODIS sensor aboard the Terra (EOS AM-1) satellite (NASA 2002).

Table 1. Surface types (T/P pass 244) and ice parameters in the region of oil rig *Sunkar* in November–December 2001.

Date	Information source	Wind direction	Wind speed (m/s)	Surface type (T/P) or ice parameters
26 Nov. 2001	T/P data	not available	not available	“open water”
30 Nov. 2001	*Khongay*	eastern	18	close ice, 5 cm, freezing, decrease of water level
1 Dec. 2001	*Khongay*	no information	no information	ice formation, 5 - 10 cm, freezing
1 Dec. 2001	*Khongay*	eastern	18	ice 12 cm
1 Dec. 2001	*Nord*	eastern	18	ice
2 Dec. 2001	*Khongay*	eastern	18	drifting ice, 2 - 5 cm
2 Dec. 2001	*Nord*	eastern	16	ice, 6 balls
3 Dec. 2001	*Nord*	eastern	10	close ice, 10 balls
6 Dec. 2001	T/P data	not available	not available	“ice”



The first appearance of close ice in the northern Caspian in winter 2001 was observed on 30 November from the *Khonga*y in the region of the *Sunkar* oil rig (Fig. 3). Decrease of near-surface air temperature (up to –9 °C) during the next few days stipulated ice formation, its spreading over the sea and increase of ice thickness. Under the influence of strong easterly winds, ice drifted rapidly westward, reaching as far west as the region of the Tulenyi Islands (Fig. 1), where it was observed on 2 December from the *Khongay.* The winds also caused a decrease in sea level in the eastern part of the northern Caspian.

Comparison of these in situ observations with T/P data for pass 244 (three points near the oil rig) shows (Table 1) that the onset of ice formation is well determined: the surface type in the region of the oil rig (and, in fact, along all track 244) was characterized as open water on 26 November 2001 and as ice on 6 December 2001. Ice edge position derived from data for T/P track 168 agrees well with its position on the same day on the MODIS image. In the eastern coastal region, surface type for ground tracks 133 (1 December) and 244 (6 December) was classed as "ice", which also corresponds to the ice distribution seen on the MODIS image.

Results

The validation described above shows that the proposed method provides robust results for discriminating between open water and ice. Applying this method for T/P data we have obtained time series of ice cover presence for each 0.05° bin for each chosen track. By averaging these data in time and space, we obtained parameters (ice presence in observations and duration of ice season) characterizing ice conditions in these two seas. For the northern Caspian, the location of T/P ground tracks made it possible to assess regional variability in three parts of the sea: western (tracks 57 and 92); central (track 168);

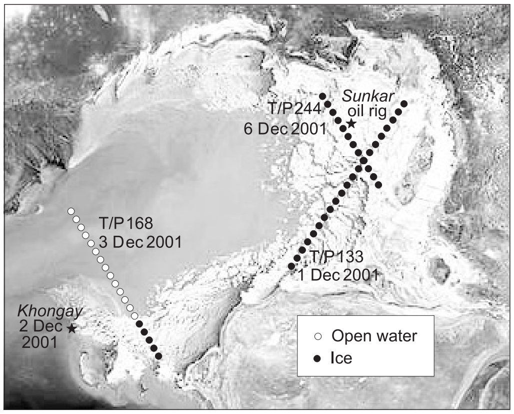


Fig. 3. Sea ice distribution from MODIS image for 3 December 2001. Surface types derived from TOPEX/Poseidon data and location of in situ ship observations.

and eastern (tracks 133 and 142). Analysis of time series of ice extent shows pronounced regional, seasonal and interannual variability.

Duration of ice period

According to our results (Table 2), in the northern Caspian and Aral seas formation of ice cover for the studied years starts mostly in November–December (in the Aral Sea, also in January), with earliest dates being 10 November for the northern Caspian and 17 November for the Aral Sea. These dates agree well with historical observations (Bortnik & Chistyayeva 1990; Terziev et al. 1992). The ice season usually terminates in March–April, though in the Aral Sea during the last four winters this has shifted to January–February. This shift resulted in a significant decrease of the duration of the ice season: from 80 - 140 to 30 - 50 days. For the northern Caspian, the duration of the ice season appears to be more stable—94 to 148 days. However, this is mostly related to the presence of ice in its eastern part, while in the western and central parts a marked decrease in duration of the ice season is also observed: from 90 - 130 to 60 - 90 in the western part, and from 100 - 140 to 30 - 70 days in the central one. This points to significant changes in recent climate conditions, which became much milder than usual in 1998–2002.

Ice presence

Presence of ice in T/P observations (in %) was calculated for the northern Caspian and Aral seas. It should be noted that these numbers represent the ratio of various surface types for observations made only in the specific regions covered by the selected T/P ground tracks (see Fig. 1) and therefore do not fully represent ice conditions for the whole sea or its parts.

The total ratio of observed ice cover varies significantly from winter to winter (Table 3, Fig. 4). These numbers show very well changes in climatic conditions for the selected regions, but direct comparison of ice cover presence for various seas should be made with caution. For example, it would be incorrect to conclude that ice conditions in the Aral Sea are more severe than in the northern Caspian (based on the comparison of percentage values of observed ice presence) because our data for the Aral Sea cover only the small central part of the sea whereas coverage of northern Caspian is much broader. However, when considering relative variations of ice cover presence, it is obvious that there are many similar features. For the first 6 - 7 winters there is a seesaw-like variability, when milder and more severe winters alternate with each other. However, this pattern changes abruptly in the last 3 - 4 winters, when there has been a sharp decrease in ice presence: from 30 - 60% to 10 - 35% in the northern Caspian and from 30 - 80% to 10 - 25% in the Aral Sea (see Table 3). This corresponds very well with the decrease of ice duration during 1998–2002 noted above.

Discussion

Interannual variability of ice conditions in the northern Caspian and Aral seas during the last decade shows a pronounced warming signal, especially during the four consecutive mild winters (1998/99 to 2001/02). Is this indicative of a long-term warming trend or is it just a series of mild winters? Comparing historical records of sea ice surface in the northern Caspian Sea and ice presence on the Aral Sea from 1950 to 1985 (Bortnik & Chistyayeva 1990; Terziev et al. 1992) and our data for 1992–2002, we see (Fig. 4) that high interannual variability has always been characteristic for both seas. There are other similar features: seesaw-like alternations of mild and severe winters, observed in our data, are also typical for most of the period ranging from 1950 to 2002. Sometimes this behaviour has overlain

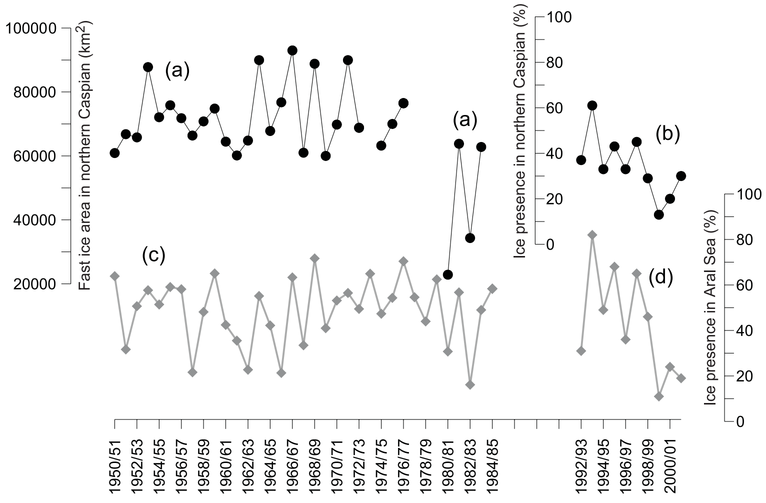


Fig. 4. Historical observations of (a) maximal fast ice area in the northern Caspian and (c) ice cover presence in the Aral Sea, and (b) TOPEX/Poseidon-derived data on ice presence for the northern Caspian and (d) the Aral Sea. Data series presented here have various scales and units of measurements. For the northern Caspian data available up to 1985 is the ice cover surface in km^2, with some gaps in observations and a change of calculation method after 1977. For the Aral Sea the historical data units are the same as for our data, but the scale is not fully comparable, as up to 1985 the data refer to the whole Aral Sea, whereas 1992–2002 data refer only to the central part of the sea.

Table 2. Duration (days) and dates of start and end of ice period in the T/P observations. Time lag of 10 days between each successive pass brings uncertainty of 5 days or less in the determination of start and end of ice period.

	Duration in various parts of northern Caspian			All northern Caspian			Aral Sea		
	Western	Central	Eastern	Duration	Start	End	Duration	Start	End
1992/93	89	110	114	114	6 Dec.	30 Mar.	80	4 Jan.	24 Mar.
1993/94	128	140	148	148	13 Nov.	10 Apr.	140	17 Nov.	5 Apr.
1994/95	99	70	109	109	4 Dec.	23 Mar.	90	29 Dec.	28 Mar.
1995/96	98	110	102	113	9 Dec.	31 Mar.	130	11 Dec.	18 Apr.
1996/97	60	80	109	110	3 Dec.	23 Mar.	80	1 Jan.	21 Mar.
1997/98	79	120	123	122	25 Nov.	28 Mar.	130	24 Nov.	2 Apr.
1998/99	59	70	113	113	17 Nov.	10 Mar.	80	6 Dec.	23 Feb.
1999/00	68	60	99	99	23 Nov.	1 Mar.	30	27 Dec.	26 Jan.
2000/01	87	30	123	123	10 Nov.	13 Mar.	50	7 Jan.	26 Feb.
2001/02	70	70	94	94	1 Dec.	5 Mar.	40	30 Nov.	9 Jan.

longer-term warming and cooling trends (such as in the case of the Aral Sea from 1965 to 1983). There were also periods of time when ice conditions were milder than usual and changed little for several consecutive years (1952–1962 and 1998–2002). However, the lack of data for 1985–1991 and the difference of scales and units of measurement currently hinder the direct comparison of our data with historical observations and therefore do not permit the confirmation or rejection of warming trend hypotheses.

Conclusion

Combining simultaneous data from nadir-looking active and passive sensors onboard the TOPEX/Poseidon satellite is a very promising avenue for studies of sea ice cover, especially in combination

Table 3. Monthly averaged values of sea ice presence (% of T/P observations) in the northern Caspian and Aral seas.

		Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Winter
Northern Caspian	1992/93	0	27	66	67	59	0	37
	1993/94	46	79	66	90	68	15	61
	1994/95	0	54	68	59	17	0	33
	1995/96	0	54	85	74	47	0	43
	1996/97	0	23	80	63	34	0	33
	1997/98	12	49	72	91	41	2	45
	1998/99	3	58	62	43	9	0	29
	1999/00	18	14	30	16	1	0	13
	2000/01	6	25	29	52	10	0	20
	2001/02	0	61	75	33	9	0	30
Aral Sea	1992/93	0	0	83	63	40	0	31
	1993/94	52	100	100	100	100	42	82
	1994/95	2	30	100	100	64	0	49
	1995/96	0	69	99	100	100	42	68
	1996/97	0	0	85	97	34	0	36
	1997/98	4	62	100	100	100	25	65
	1998/99	0	100	100	75	0	0	46
	1999/00	0	15	50	0	0	0	11
	2000/01	0	4	48	94	0	0	24
	2001/02	3	91	17	2	0	0	19

with other direct or indirect observations. High spatial along-track and temporal resolution, independence from weather conditions, robustness of discrimination between open water and ice appear as obvious advantages. One drawback is the relatively coarse cross-track coverage of T/P, limiting such studies to specific regions. This situation may be improved by using additional data sets from other satellites with similar set of sensors, such as ERS-1 and -2 and the recently launched Jason-1 and ENVISAT satellites, as well as passive microwave data from imaging radiometers (SMMR and SSM/I).

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