Seasonal and long-term sea level variability in the marginal seas of the Arctic Ocean

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One of the parameters useful for monitoring large-scale climate variability in the Arctic Ocean is sea level. It integrates virtually all static and dynamic processes in the hydrosphere and atmosphere of the Arctic. Previously unavailable mean monthly sea level data at 44 coastal and island stations in the Kara, Laptev, East Siberian and Chukchi seas covering years from 1950 to 1990 were used to analyse seasonal and inter-annual variability. Sea level has a significant annual cycle with an average seasonal amplitude (from peak to peak) in the coastal zone of the Arctic seas on the order of 20 - 30 cm. The analysis of inter-annual and inter-decadal changes has shown that at nearly all stations in the Kara, Laptev, East Siberian and Chukchi seas from the beginning of the 1950s through the end of 1980s there is a positive trend in sea level variability. The main contribution to the sea level rise was in the 1980s; on average for the coastal zone of Siberian shelf the sea level in the 1980s was 5 - 6 cm higher than in the previous decades. A reasonable agreement between observed decadal mean sea level values and the results of diagnostic model simulations suggests that this rise in the Arctic seas is connected with the reorganization of large-scale circulation of the Arctic Ocean, rather than the regional lowering of the coasts, as has been suggested previously.

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Influenced by the integration of a number of physical processes in the environment, sea level can serve as a representative parameter for monitoring climate changes in the Arctic (Pavlov & Stanovoy 1997). The major factors shaping sea level variability are changes in water density, the reorganization of the thermohaline circulation and the modification of atmospheric dynamics.

Seasonal and inter-annual sea level variability was analysed using a virtually continuous 40-year (1950–1990) time series of mean monthly data at 44 island and coastal stations in the Kara, Laptev, East Siberian and Chukchi seas (Table 1). These stations are irregularly distributed over the coastal zone of the Russian Arctic seas. The largest number of stations was located in the Kara Sea; the fewest were in the Chukchi Sea. Only those Chukchi Sea stations located in the Russian coastal zone were subject to analysis.

Tide gauges at most coastal and island stations were not connected with the geodetic network, and therefore only relative sea level values were measured at these stations. In the analysis of seasonal and inter-annual variability, we have first removed the mean sea level value for each station, calculated over the entire period of observations.

Previous analyses of seasonal and inter-annual sea level variation have been conducted for different Siberian shelf stations by Dvorkin et al. (1978), Pavlov (1998) and Pavlov & Pavlov (1999). However, Dvorkin et al. (1978) used observations up to the mid-1970s, so their results did not take into account modern sea level trends. Pavlov (1998) and Pavlov & Pavlov (1999) have conducted a similar analysis for only selected stations in the Laptev and East Siberian seas.

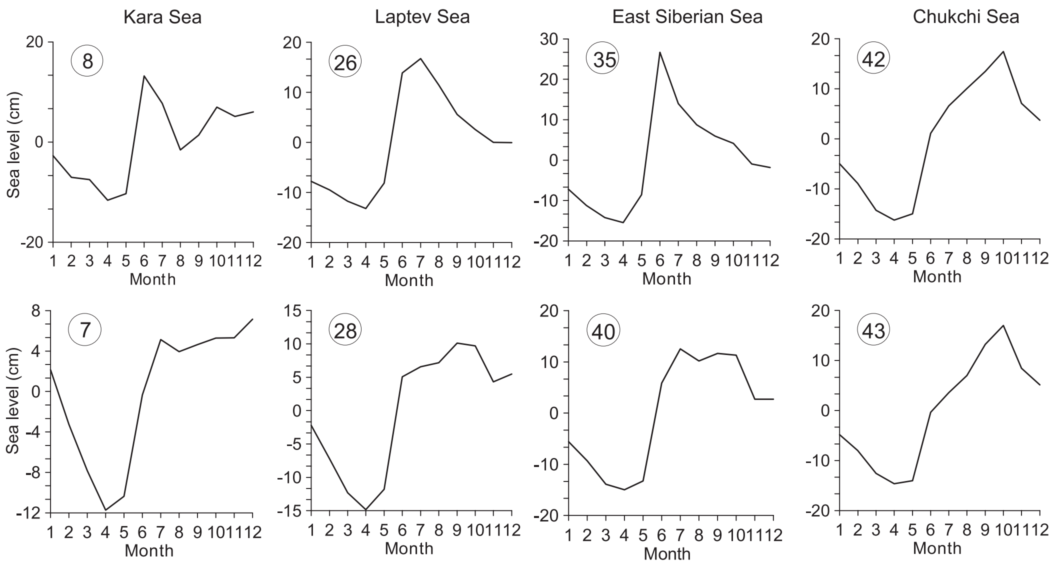

Fig. 1. Seasonal sea level variability in the Kara, Laptev, East Siberian and Chukchi seas. Geographical locations are given in Table 1, in accordance with the numbers used here.

Results

Seasonal variability

Figure 1 shows typical examples of seasonal variability of the monthly mean sea level in the coastal zone of the Siberian marginal seas. At all the stations the minimum values were observed in April. Sea level sharply increases from May, reaching its maximum values in summer and autumn.

In the Kara Sea the absolute sea level maximum is observed in June or July at most stations located along the Siberian coast and especially near river mouths (Fig. 1). Some stations have annual absolute maxima in October or December. However, these stations also show local maxima in the summertime. It was shown by Pavlov & Pavlov (1999) that extreme values were related to the appearance of a baroclinic coastal current in summer. The summertime baroclinic coastal current is not only a local phenomenon of the Kara Sea but an important feature of the water circulation in all the Siberian seas (Weingartner et al. 1999; Pavlov 2001a). This current is caused by large density gradients because of fast ice melting and increased freshwater inflow. High correlation between sea level and water density throughout the year (Pavlov & Pavlov 1999) suggests that the main contribution to the seasonal cycle of sea level variations results from changes of the thermohaline conditions and the related steric expansion and reorganization of the general circulation in the Arctic Ocean.

Calculation of the monthly mean steric sea level at the station near Enisey Bay, based on annual observations of temperature and salinity which were carried out in 1961, shows good agreement with the observed sea level for the May–September period (Pavlov 2001b). The amplitude (from peak to peak) is close to the observed amplitude at the nearest station, Dikson. This implies that the major cause of the dramatic increase of the sea level near the mouths of the big Siberian rivers in June–July is steric expansion resulting from increased river discharge at this time (which our observations suggest is caused by increased snowmelt due to higher spring–summer temperatures). The main contribution to steric expansion (about 90 %) is the reduction of salinity in summertime.

The extremes in autumn through early winter are caused by intensification of atmospheric circulation over the Arctic Ocean in that period of the year. The mean amplitude (from peak to peak) of the seasonal sea level oscillations in the Kara Sea is 21.4 cm. The maximum amplitude was 33.7 cm and was observed at the Ust-Kara station.

Seasonal variability in the Laptev Sea is nearly the same as in the Kara Sea. Minima are observed in April and maxima in June, July or October

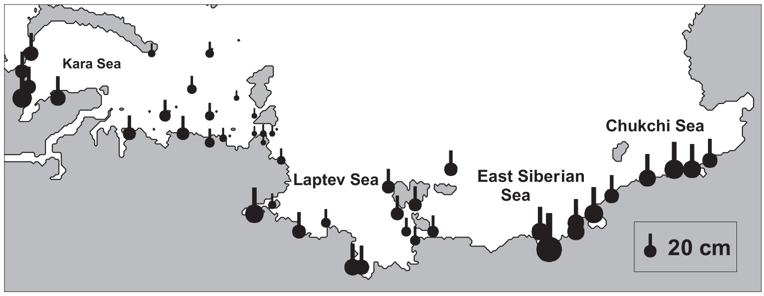

Fig. 2. Spatial variations in amplitude (from peak to peak) of the annual cycle of the sea level.

depending on the region (Fig. 1). In contrast to the Kara Sea, the December maximum is completely absent in the Laptev Sea. The mean amplitude of the annual sea level cycle in the Laptev Sea is 23.4 cm. The maximum amplitude of 32.6 cm was observed at the Kosistiy station.

The absence of the absolute October sea level maximum in the East Siberian Sea (Fig. 1) is a specific feature of this region. Local maxima were observed at some stations in October. The absolute maximum at all the stations is observed in July. The minimum sea level values are observed, as in the previous cases, in April. The mean sea level amplitude in the East Siberian Sea was 29.8 cm. The maximum amplitude (42.2 cm) was observed at the Ambarchik station.

Stations in the Chukchi Sea show an absolute sea level maximum in October (Fig. 1). Small local extrema were observed at the Netten and Shmidt stations in June and July. The mean amplitude of the annual sea level cycle in the Chukchi Sea is 31.0 cm. The maximum amplitude of 33.7 cm was observed at the Vankarem station.

Figure 2 shows the geographical variation in the seasonal sea level amplitude. Maximum values of the amplitude are observed along the western coast of the Kara Sea, in bays and gulfs of the Laptev Sea, along the eastern coast of the East Siberian Sea and in the western Chukchi Sea. The minimum amplitude of seasonal variability is observed at the island stations in the northern Kara and Laptev seas.

The amplitude of seasonal variability in the Arctic seas appears to depend on latitude (Fig. 3). The maximum amplitudes occur in the southernmost regions, with minima observed at stations further to the north. A possible explanation for this is the stronger steric expansion of sea level in southern regions due to strong freshwater and warm-up of water masses in summer.

Table 1. Names, geographical locations and time periods of the observational stations in the coastal zone of the Kara, Laptev, East Siberian and Chukchi seas.

Station no.	Observation stations	Longitude (N)	Latitude (E)	Time period
1	Bolvanskiy Nos	59.06	70.45	1951–1987
2	Yugorskiy Shar	60.75	69.81	1950–1987
3	Zhelaniya	63.56	76.95	1951–1985
4	Ust Kara	64.51	69.25	1950–1989
5	Kharasovey	66.81	71.13	1954–1992
6	Amderma	61.68	69.77	1950–1987
7	Vize	76.98	79.50	1953–1989
8	Dikson (Bay)	80.40	73.50	1950–1989
9	Uedineniya	82.23	77.50	1953–1989
10	Izvestiya CEC	83.08	75.53	1954–1989
11	Sterligova	88.90	75.53	1950–1989
12	Isachenko	89.20	77.15	1954–1989
13	Golomjaniy	90.61	79.55	1954–1989
14	Pravdy	94.28	76.26	1950–1989
15	Russkiy	96.43	77.16	1951–1980
16	Krasnoflotskie	98.71	78.63	1954–1987
17	Geyberg	101.51	77.60	1951–1989
18	Solnechnaya	103.26	78.20	1951–1989
19	Cheliuskin	104.28	77.71	1950–1985
20	Maliy Taimyr	106.81	78.08	1950–1990
21	Kosistiy	109.73	73.66	1954–1989
22	Andrey	111.45	76.81	1951–1990
23	Preobrazheniya	112.93	74.66	1951–1990
24	Terpiay-Tumsa	118.66	73.53	1956–1990
25	Dunay	124.50	73.93	1951–1987
26	Tiksi	128.91	71.58	1949–1990
27	Muostakh	130.01	71.55	1951–1990
28	Kotelniy	137.90	76.00	1951–1990
29	Sannikov	138.90	74.66	1950–1990
30	Kigiliakh	139.88	73.35	1951–1990
31	Sviatoy Nos	140.73	72.83	1951–1987
32	Bunge Land	142.11	74.88	1951–1987
33	Shalaurova	143.93	73.18	1950–1990
34	Zhokhova	152.83	76.15	1959–1990
35	Ambarchik	162.30	69.56	1950–1991
36	Chetyrokh-stolboviy	166.58	69.51	1951–1991
37	Rua-Chau	166.58	69.51	1950–1989
38	Ayon	167.98	69.91	1954–1991
39	Pevek	170.60	69.75	1950–1991
40	Billingsa	175.76	69.88	1953–1991
41	Shmidt Cape	180.51	68.91	1950–1990
42	Vankarem	184.16	67.83	1950–1991
43	Koluchin	185.36	67.48	1950–1991
44	Netten	188.06	66.95	1950–1991

Table 2. Linear trends of the inter-annual sea level variation and anomalies in the Kara, Laptev, East Siberian and Chukchi seas. Anomalies for each station were calculated as deviations from mean (for four decades) sea level. Geographical locations are given in Table 1.

Stations	Coefficients of the linear trend 1950–1989	Sea level anomalies (cm)			
		1950s	1960s	1970s	1980s
Kara Sea					
Amderma	0.03	-1.80	1.18	-0.70	1.32
Bolvanskiy Nos	0.07	-0.98	0.42	-1.82	2.39
Cheluskin	0.07	-0.89	0.73	-2.21	3.36
Solnechnaya	0.46	-7.82	-0.36	-0.52	8.70
Dikson	0.00	-0.89	1.04	-0.67	0.53
Geyberga	0.19	-3.16	0.19	-1.41	4.39
Zhelaniya	-0.43	-0.96	4.47	-2.18	-3.51
Golomyaniya	0.06	-2.97	2.70	-2.68	2.95
Kharasovey	0.17	-4.26	0.32	-2.74	6.67
Isachenko	0.35	-1.47	-2.44	1.26	2.65
Izvestiy CEC	0.10	-2.05	0.64	-0.1	1.41
Krasnoflotskaya	0.22	-3.71	0.00	-0.27	3.98
Pravdi	0.25	-3.62	0.08	-2.89	6.43
Sterligova	0.17	-2.35	-0.18	-1.75	4.26
Yugorskiy Shar	0.14	-0.94	1.08	-0.86	0.72
Uedineniya	0.03	-3.84	1.22	1.28	1.35
Ust-Kara	0.06	0.01	-0.67	-1.38	2.06
Vize	0.06	-0.88	0.58	-1.36	1.66
Averaged	0.111	-2.316	0.626	-1.162	2.851
Laptev Sea					
Andrey	0.33	-6.60	0.62	0.87	5.10
Dunay	0.09	-0.42	-0.69	-2.54	3.64
Kigilyakh	-0.04	3.32	-1.00	-3.15	0.84
Kosistiy	-0.71	3.94	3.45	-10.45	3.06
Kotelniy	0.48	-8.06	-0.73	1.22	7.57
Maliy Taymir	0.24	-5.04	0.67	-0.39	4.76
Muostakh	0.31	-3.47	0.20	0.43	3.70
Preobrageniya	0.07	-0.90	0.17	0.68	1.41
Sannikova	0.06	0.23	-0.68	-1.60	1.43
Sviatoy Nos	0.21	-1.89	-1.37	-3.70	6.95
Terpiya Tumsa	0.23	-3.42	0.24	-0.64	3.81
Tiksi	0.14	-1.26	-0.49	-1.37	3.13
Averaged	0.123	-1.963	0.084	-1.904	3.783
East Siberian Sea					
Cheryriokh-stplboviy	0.11	3.54	-3.35	-4.74	4.55
Ambarchik	0.2	1.08	-4.41	-2.70	6.02
Ayon	0.00	5.88	-2.39	-5.86	2.37
Billingsa	0.15	3.32	-3.81	-4.13	4.62
Bunga	0.23	-2.89	-1.20	0.36	3.73
Zhokhova	0.17	4.08	-1.50	-5.32	2.73
Pevek	0.21	1.44	-4.28	-2.86	5.69
Rua-Chau	0.05	3.83	-4.00	-3.93	4.10
Shalaurova	0.05	0.70	1.23	-2.28	0.35
Averaged	0.130	2.331	-2.633	-3.495	3.796
Chukchi Sea					
Koluchin	0.52	-2.72	-7.16	0.14	9.74
Netten	0.33	-3.35	-1.95	-3.15	8.45
Shmidt Cape	0.32	-2.8	-0.30	-3.60	6.70
Vankarem	0.50	-6.82	-3.12	-1.12	11.05
Averaged	0.418	-3.921	-3.131	-1.931	8.984

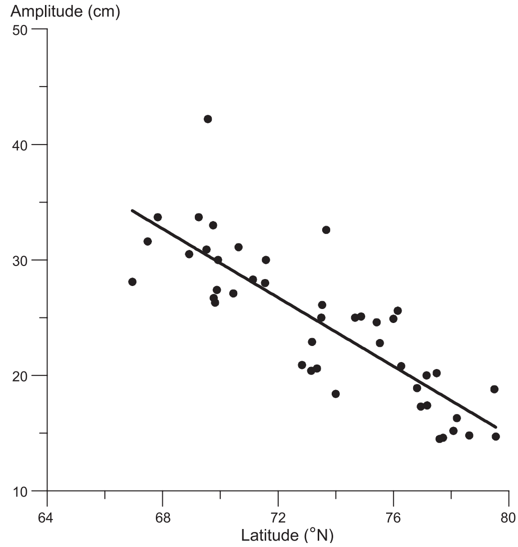

Fig. 3. The annual amplitude of sea level plotted against the location (latitude) of observational station.

Inter-annual variability

Positive trends in inter-annual sea level variability at the almost all stations in the coastal zone of the marginal Arctic seas were observed from the beginning of the 1950s until the end of the 1980s (Table 2). Trends of *decreasing* annual mean sea levels were observed at only three of the 44 stations: Zelania in the Kara Sea, Kigiliakh and Kosistiy in the Laptev Sea in the same period. The negative trend at these stations could be explained by local uplift connected with the geological processes in that region or by instrumental errors of observations. Unfortunately, insufficient information about local environmental conditions and methods of observations prevents us from offering a precise explanation of such sea level variability at these three stations. Figure 4 shows typical examples of inter-annual variability of the annual mean sea level in the coastal zone of the marginal seas of the Siberian shelf. The magnitudes of inter-annual variability of the annual mean sea level values in the Kara and Laptev seas are comparable with the amplitudes of the seasonal variation. In the East Siberian and Chukchi seas, inter-annual variability is greatest, reaching 40 cm and more.

In the three decades spanning the beginning of the 1950s to the end of the 1970s, the positive sea level trend was not as pronounced as it was in

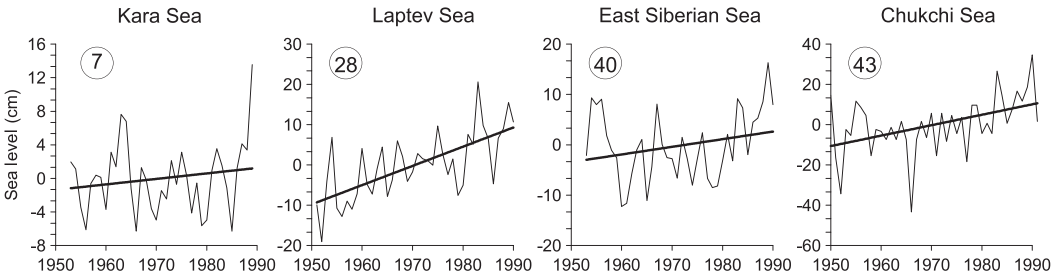

Fig. 4. Seasonal variability of sea level (thin line) and the linear trend (bold line) in the Kara, Laptev, East Siberian and Chukchi seas. Geographical locations are given in Table 1, in accordance with the numbers used here.

the 1980s. The majority of the Kara Sea stations and only half of the Laptev Sea stations have positive trends in this period of the 1950s through the 1970s. However, averaged trends for the Kara and Laptev seas were positive as well (0.07 cm/year and 0.06 cm/year for Kara and Laptev seas, respectively). For calculations of the averaged trends in the Kara and Laptev seas we did not use data from stations Zelania, Kigiliakh and Kosistiy because their quality is doubtful, as is mentioned above. Almost all stations in East Siberian Sea show a negative trend (-0.219 cm/year on average) over the 1950s–1970s. In contrast, all the Chukchi Sea stations showed a positive trend in this period (0.108 cm/year on averaged).

In the Kara Sea (Table 2) in the 1950s, the negative anomaly of the sea level was -2.32 cm on average. In the 1960s the sea level increased on average by 3 cm and in the Kara Sea there was a weak (0.63 cm) positive sea level anomaly. In the 1970s the level of the Kara Sea again lowered and the negative anomaly reached on average -1.16 cm. In the 1980s, the sea level rise was more than 4 cm and the positive anomaly in this decade reached the maximum value (2.85 cm). A similar pattern occurred in the Laptev Sea, with the only difference that in the 1980s the sea level there increased more significantly (by nearly 6 cm) compared with the previous decades. In the East Siberian Sea the positive anomaly that was observed in the 1950s was replaced with a negative one in the next two decades. But in the 1980s there was a sharp sea level increase (more than 7 cm). In the Chukchi Sea the negative sea level anomalies were preserved during the three decades from the 1950s through the 1970s. In the 1980s, the sea level rose (nearly 11 cm on average) and the positive anomaly became 8.98 cm. Cal-

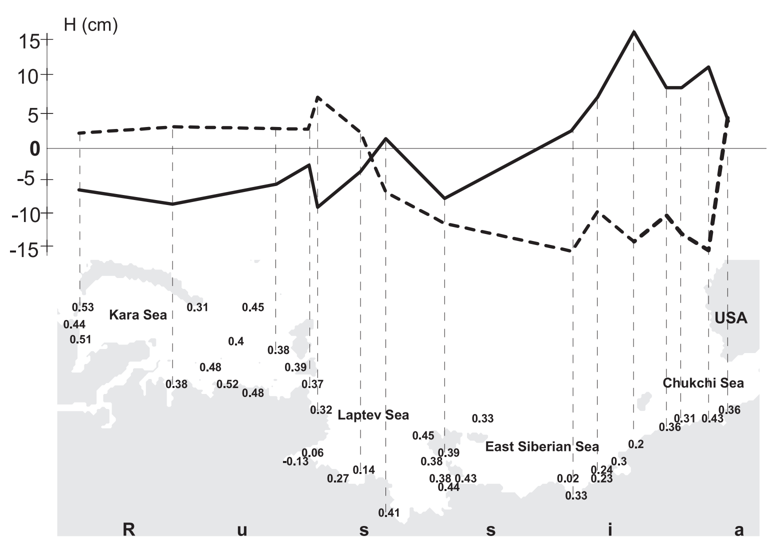

Fig. 5. Anomalies of the annual mean sea level when cyclonic (solid line) and anticyclonic (dashed line) regimes prevail. Values indicate correlation coefficients between winter NAO index and sea level in February.

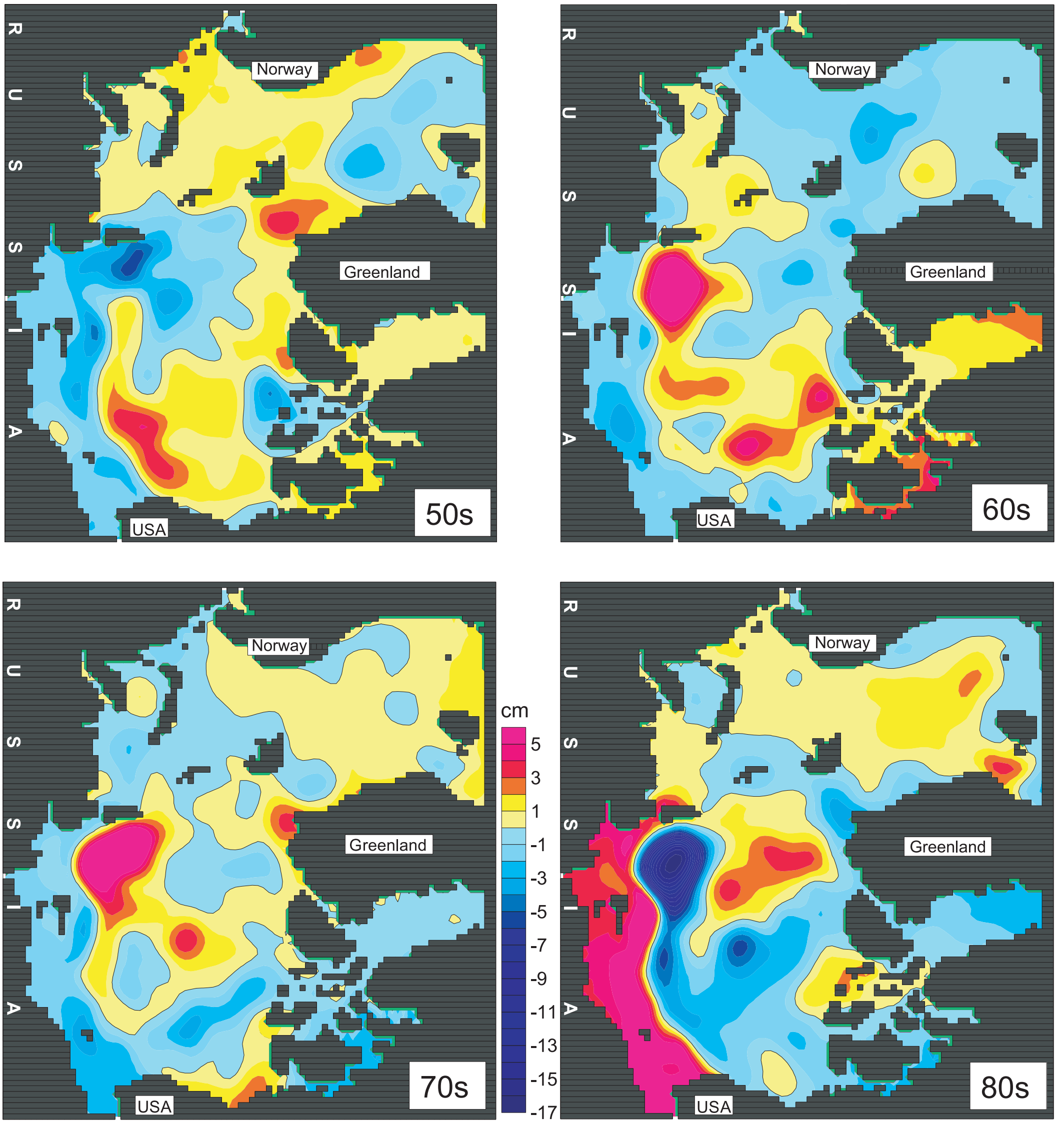

Fig. 6. Decadal mean anomalies of the sea level (cm) of the Arctic Ocean (modelling results) for the 1950s, 1960s, 1970s and 1980s.

culation of the decadal sea level anomalies and trends therefore reveal that an especially strong sea level increase in the coastal zones of all the Siberian shelf seas was in the 1980s (Table 2).

Discussion

What is the reason for such a pattern of long-term variability of the sea level in the marginal Arctic seas? Major aspects of the sea level change problem, methods of sea level change detection, modelling and interpretation of sea level variability are discussed in publications by Pugh (1987), National Research Council (1990), Emery & Aubrey (1991), Woodworth et al. (1992), Baker (1993), Woodworth (1993), Gornitz (1995), Peltier (1999) and many others. Most of the stations in the Arctic Ocean show a significant sea level rise. This sea level increase could be a manifestation of global warming in the Arctic, together with a decrease of sea ice extent (Johannessen et al. 1999) and ice thickness (Rothrock et al. 1999), air temperature rise (see IPCC at www.ipcc.ch;

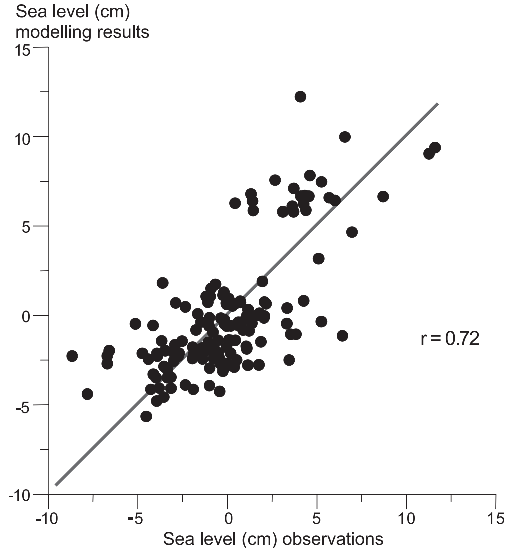

Fig. 7. Correlation between observed and calculated values of decadal mean sea level at the observational points.

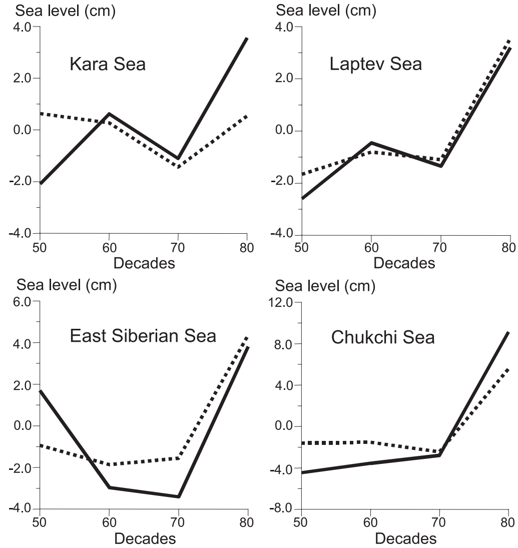

Fig. 8. Inter-decadal variability of the average sea level for the Kara, Laptev, East Siberian and Chukchi seas: observed, solid line; modelled, dashed line.

Levitus et al. 2001), warming of Atlantic waters (Morison et al. 1998; Steele & Boyd 1998), increased river runoff and atmospheric circulation changes (see www.ipcc.ch).

The positive trend of sea level increase in the Arctic seas was noted earlier by Dvorkin et al. (1978). Analysing data from the most representative stations along the Siberian coast, Dvorkin et al. explain the increase by suggesting that the Arctic seas' coasts are lowering. This is not supported by the results of the present study, which shows that there are opposite trends at some stations in some months. The trend of sea level increase in the Arctic seas can be more correctly explained by changes in the water properties and large-scale circulation of the Arctic Ocean.

Shpaykher et al. (1972) proposed that physical processes (including sea level) strongly depend on the circulation of the Arctic Ocean. Figure 5 shows that due to the dominance of the cyclonic circulation above the Arctic Ocean, the sea level in the Laptev, East Siberian and Chukchi seas is high and the level in the Kara Sea is low. In years when the circulation is predominantly anticyclonic there is an opposite situation. However, the analysis of the relationship between winter North Atlantic Oscillation (NAO) index and interannual sea level elevations in the Arctic seas has shown that the correlation coefficients are significant, but not high (Fig. 5). At the same time, in Barentsburg on Fram Strait, where the barotropic circulation dominates (Verduin 1999), the correlation coefficient between winter NAO index and sea level elevations is high ($r = 0.78$) according to our calculations. Recently, the contributions of wind and baroclinic components of the circulation to inter-annual variability of sea level in the Laptev Sea were analysed in Pavlov & Pavlov (1999). It showed that the baroclinic component predominates.

To estimate the contribution of baroclinic circulation into the long-term variability of the sea level of the marginal Arctic seas, mean decadal fields of level using a numerical model were simulated (Pavlov & Pavlov 1999). For the diagnostic simulation, mean decadal 3-D fields of water temperature and salinity of the Arctic Ocean for the years 1950–1980 (Arctic Cliomatology Project 1998) were used. Figure 6 shows the anomalies of the sea level for each of four decades (1950s, 1960s, 1970s and 1980s) obtained from the model. The highest positive anomaly in the 1980s is located in the marginal seas along the Siberian coast. The maximum positive trend (about 8 cm for 40 years) is in the northern parts of the East Siberian and Chukchi seas. There is a compensating negative sea level anomaly over the continental slope. The maximum negative trend is located in the northern part of the Laptev Sea.

The comparison between simulated and observed mean decadal sea level at 44 coastal and island stations in the Arctic seas shows very good agreement (Fig. 7).

The typical feature of the sea level's inter-decadal variability is the sharp increase of the sea level in the shelf zone of the Kara, Laptev, East Siberian and Chukchi seas (Fig. 8). In the Kara Sea during the 1980s, the level also increased, but not as significantly as in more eastern regions of the Arctic Ocean.

Conclusion

The sea level in the coastal zone of the marginal seas of the Arctic Ocean has a significant annual cycle. The amplitude (from peak to peak) of the seasonal sea level variability is 20 - 30 cm on average.

The good agreement between observed decadal mean values of the sea level and the results of diagnostic simulations gives grounds to believe that the tendency of the sea level rise in the Arctic deas in the 1980s is connected with changes in the large-scale circulation of the Arctic Ocean.

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