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Storm Surges in the Southern Baltic Sea (Western and Central Parts)

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PREFACE

Both the German and Polish Baltic Sea coasts are threatened by storm surges. This monograph on storm surges in the western and central parts of the southern Baltic Sea coast was prepared on the initiative of the Polish-German Working Group W-1 on hydrology and hydrogeology in the German-Polish boundary waters. It is a co-operation project between the Institute of Meteorology and Water Management (Instytut Meteorologii i Gospodarki Wodnej - Oddział Morski (IMGW), Gdynia) in Poland and the Federal Maritime and Hydrographic Agency of Germany (Bundesamt für Seeschifffahrt und Hydrographie (BSH), Rostock - Hamburg).

The first part of the monograph provides a general description of the hydrological and meteorological conditions leading to storm surges, including some statistical data. The analysis is based on the data of 73 selected storm surge events from the years 1976 – 2000 and on long-term series, some of which date back as far as 1870.

The second part of the monograph provides descriptions of the 17 most dangerous storm surges of the total of 73 surges selected in the period from 1976 – 2000. The description of each surge includes

a) the development of meteorological conditions, focusing on the atmospheric pressure pattern and wind field forcing the surface water, and
b) the behaviour of the sea level at particular water gauges.

The monograph was prepared using available publications on the subject as well as archived data at IMGW and BSH.

The study was funded by statutory contributions available to BSH and IMGW, funds from scientific projects of the European Union (SELF, ESEAS-RI), NATO (EST.CLG978911), the State Committee for Scientific Research, and financial resources of IMGW.

The descriptions of meteorological conditions during the storm surges of 1976-1994 are based on work done by mgr. L. Wójcik, dr. M. Ziemiański, mgr. G. Łabieniec and mgr. I. Lelątko within the framework of the SELF project (EU FP3).

1. GENERAL DESCRIPTION OF STORM SURGES

This monograph on the most important storm surges in the western and central parts of the southern Baltic Sea coast in the period from 1976 to 2000 was prepared in co-operation between the Federal Maritime and Hydrographic Agency of Germany (Bundesamt für Seeschifffahrt und Hydrographie, Rostock - Hamburg) and the Institute of Meteorology and Water Management (Instytut Meteorologii i Gospodarki Wodnej - Oddział Morski, Gdynia) following the conclusion of the Polish/German treaty on water management in the boundary waters. On the basis of this treaty, the forecasting and warning services of the two countries co-operate closely within the framework of a Polish/German working group W-1 for hydrology and hydrogeology in the boundary waters. This includes the exchange of hydrological data, information about coastal defence measures, sea-ice service, and joint scientific studies.
Because of the separation of meteorological and hydrological competences in Germany, the main work on the preparation of this monograph was carried out by the maritime branch of IMGW.

1.1 Brief review of scientific contributions

The catalogue of storm surges on the Polish coasts in the years 1951-1975 (Majewski ed., Dziadziuszko and Wiśniewska 1983) occupies an important position in the oceanographic literature of Poland. It describes sea level variations at three Polish gauges - Kołobrzeg, Ustka and Władysławowo - during 75 of the most interesting surges and also provides descriptions of the atmospheric conditions, e.g. pressure pattern, wind speeds and directions (this monograph is a continuation of the study published in 1983). A comparable paper discussing storm surges on the German Baltic Sea coast does not exist. The only similar publication is „Untersuchungen über Sturmflutwetterlagen an der deutschen Ostseeküste" (Investigation of weather conditions causing storm surges on the German Baltic coast) by Erich Kohlmetz (1964), which covers the events from 1872 to 1961.
Among other German and Polish contributions, Wielbińska (1966) gave some examples of the dominant influence of strong onshore wind on coastal surges. The atmospheric circulation patterns accompanying storm surges on the Polish coast were also investigated by Wiśniewska (1978).
Both the Polish and German bibliographies of the second half of the 20th century contain a series of studies on storm surges, which were published in various journals, as conference papers, or at relevant institutions. Relevant papers were published, e.g., by Kostrzewa et al. (1983), Majewski (1989), Malicki and Wielbińska (1992), Baerens et al. (1994), Hupfer et al. (1994), Neemann (1994), Dziadziuszko and Malicki (1995), Sztobryn et al. (1995), MBLU (1996), Beckmann (1997), Meinke (1998), Sztobryn (2000), Kowalska (2001), Stanisławczyk (2001, 2002) and Hupfer et al. (2003). Many of these papers focus on physics and statistics without, however, providing detailed descriptions of individual storm surges. Adequate documentation is only available on a few exceptional events. This ongoing loss of information has not been markedly reduced until the end of the 20th century, following the introduction of electronic archiving of meteorological and hydrological records. In this respect, the present study closes a gap in the available descriptions of Baltic storm surges.

1.2 Definition of a storm surge

A storm surge (after Hydrological Aspects of Combined Effects of Storm Surges and Heavy Rainfall on River Flow, WMO - No. 704, Geneva 1988) has been defined as a rapid change of sea level above the level that would be observed at the same time and place without the impact of stormy winds. In the International Glossary of Hydrology (WMO - Geneva 1992), a storm surge has been defined as an elevation of the sea level caused by the passage of a low pressure centre.
The exact definition of storm surges is a function of probability, but on the German Baltic coast a more common definition of a storm surge is the occurrence of a water level at least 1m above the generalized mean sea level. In terms of tide gauge data, this means at least

600 cm. The zero level of tide gauges is PN=NN-500 cm in Schleswig-Holstein and in Poland, and PN=HN-514 cm in Mecklenburg-Vorpommern.
In Poland, Majewski et al. (1983) defined a storm surge as a hydrological situation in which the sea level reaches or exceeds 570 cm (for comparison: the alarm level at Świnoujście and Kołobrzeg is set at 580 cm, and at Wismar, Warnemünde and Sassnitz at 600 cm).
On that basis, 73 storm surges from the period 1976-2000 (Table 1.1.) were selected during which a level of 590 cm had been either reached or surpassed at Wismar, Warnemünde and Sassnitz, and a level of 570 cm at Świnoujście and Kołobrzeg. The selection of events meeting this requirement with respect to the German water gauges was done by H.-J. Stigge at BSH Rostock, and with respect to the Polish water gauges by M. Sztobryn, B. Kowalska, K. Krzysztofik and A. Kańska.

Table 1.1. Calendar of storm surges in the western and central parts of the southern Baltic Sea coast in 1976-2000

No.	Gauge Świnoujście			Daily reference level in cm	Maximum value of the surge in cm				
	Beginning of surge	End of surge	Duration of surge in hours		Wismar	Warnemünde	Sassnitz	Świnoujście	Kołobrzeg
1	03.01.76	04.01.76	39	548	640	630	608	628	616
2	17.01.76	17.01.76	13	550	598	590	599	616	600
3	24.12.76	27.12.76	61	490	611	593	590	605	602
4	03.01.78	05.01.78	39	523	620	602	591	583	602
5	28.11.78	01.12.78	65	554	607	596	595	-	592
6	13.02.79	16.02.79	85	510	663	629	585	570	532
7	11.12.79	12.12.79	43	534	627	611	583	575	563
8	28.11.80	30.11.80	50	527	598	587	582	588	573
9	16.12.80	17.12.80	14	557	581	577	574	570	584
10	05.11.81	09.11.81	93	535	594	588	586	600	594
11	30.11.81	02.12.81	57	552	600	588	581	591	581
12	06.01.82	08.01.82	48	514	616	598	590	585	574
13	19.01.83	20.01.83	34	577	634	617	624	623	640
14	21.01.83	22.01.83	22	553	567	564	577	573	585
15	31.01.83	31.01.83	19	556	572	567	587	580	586
16	02.02.83	05.02.83	24	568	613	608	619	599	627
17	06.02.83	09.02.83	81	553	651	632	605	583	579
18	25.09.83	25.09.83	17	559	600	592	601	591	600
19	27.11.83	29.11.83	39	552	646	634	619	611	612
20	29.11.83	01.12.83	44	561	606	592	578	582	565
21	09.12.83	11.12.83	34	530	613	594	590	601	596
22	09.01.84	09.01.84	22	561	615	602	602	596	595
23	20.01.86	20.01.86	11	537	564	556	561	590	588
24	20.10.86	21.10.86	20	509	619	606	555	590	599
25	19.12.86	21.12.86	46	520	641	627	609	613	612
26	22.12.86	23.12.86	47	545	603	592	577	580	577
27	08.01.87	10.01.87	34	509	611	600	605	612	609
28	11.01.87	13.01.87	82	519	673	642	614	599	552
29	02.11.88	04.11.88	48	496	630	616	610	582	590
30	29.11.88	01.12.88	38	522	647	628	620	621	642
31	14.12.88	15.12.88	39	536	611	600	583	597	600
32	19.12.88	20.12.88	23	534	620	607	594	604	604
33	24.12.88	25.12.88	21	554	585	576	572	593	597
34	31.12.88	01.01.89	21	509	597	580	581	585	587
35	02.10.89	04.10.89	44	519	610	601	576	600	592

36	15.11.89	16.11.89	38	515	628	612	584	580	584
37	26.11.89	27.11.89	23	512	581	575	565	570	571
38	27.11.89	28.11.89	23	515	622	604	603	605	609
39	07.12.89	07.12.89	26	513	633	615	614	605	623
40	02.03.90	03.03.90	25	564	584	582	577	583	588
41	12.03.90	14.03.90	33	551	570	568	580	584	588
42	24.12.91	25.12.91	40	527	581	568	575	583	590
43	27.12.91	28.12.91	24	547	617	599	589	586	593
44	30.12.91	31.12.91	18	549	565	555	573	571	582
45	12.01.92	13.01.92	27	541	566	558	590	573	587
46	17.01.92	18.01.92	27	532	613	598	636	616	640
47	16.02.92	17.02.92	33	535	624	604	585	580	580
48	23.01.93	23.01.93	12	550	583	573	563	578	586
49	25.01.93	26.01.93	17	570	595	589	575	603	615
50	19.02.93	20.02.93	26	521	585	584	572	587	571
51	21.02.93	22.02.93	67	520	656	631	624	641	622
52	25.12.93	26.12.93	34	535	616	605	579	573	566
53	28.01.94	29.01.94	37	540	592	584	566	577	576
54	02.01.95	03.01.95	51	541	642	629	615	620	616
55	11.01.95	13.01.95	60	528	610	592	575	581	578
56	27.03.95	28.03.95	19	552	602	597	575	577	581
57	07.04.95	09.04.95	38	541	629	618	608	608	620
58	30.08.95	01.09.95	32	544	613	599	581	602	584
59	02.11.95	05.11.95	51	536	702	660	637	661	640
60	06.11.95	07.11.95	26	524	606	586	585	571	572
61	17.11.95	18.11.95	26	531	590	580	573	571	577
62	11.04.97	13.04.97	117	521	620	609	604	600	612
63	02.10.97	03.10.97	16	546	586	579	560	574	576
64	03.11.97	03.11.97	16	531	610	591	593	576	584
65	20.01.98	21.01.98	40	524	598	593	579	583	582
66	30.01.98	01.02.98	41	503	623	608	580	585	584
67	16.02.98	17.02.98	27	525	595	576	570	582	581
68	05.03.98	06.03.98	11	542	577	583	575	594	582
69	06.11.98	07.11.98	26	536	556	554	552	576	592
70	05.02.99	07.02.99	57	519	580	578	575	588	580
71	24.02.99	25.02.99	20	550	570	571	564	576	582
72	15.12.99	16.12.99	28	553	583	576	571	572	578
73	17.01.00	22.01.00	37	537	608	608	591	600	601

* The storm surge of January 1987 is described in chapter 6 as a storm surge with 2 peaks

The definition of a storm surge provided by Majewski (1989) gives a very good impression of the dangers of a storm surge but fails to specify the water level that would exist "at a given time and place without stormy onshore winds affecting sea levels at the coast ...". Therefore, in the 1990s, a characteristic indicator called “daily reference level” (Sztobryn, Kańska, Krzysztofik, Kowalska) was included in the specification of storm surges at the Hydrological Forecasting Office of the maritime branch of IMGW in Gdynia. This one-dimensional parameter [cm] is described in chapter 3.2.
The parameter allows the determination of the beginning and expected end of a storm surge, and thus its duration, which is highly useful in flood combating.
In selecting the 73 storm surges that have been analysed in this monograph, the precise time at which the sea level exceeded the above parameter was considered the beginning of the storm surge.

1.3 Western and central parts of the southern coast of the Baltic Sea

The purpose of this monograph is a description of the most dangerous storm surges observed in the western and central parts of the southern Baltic Sea (Fig.1.1.). The area covering the central and eastern parts of the German Baltic coast is represented here by the water gauges at Wismar, Warnemünde and Sassnitz, and the western part of the Polish coast is represented by the water gauges at Świnoujście and Kołobrzeg.

Fig. 1.1. Western and central parts of the southern Baltic Sea coast

The German Baltic Sea coast, located at the western edge of the Baltic length axis, is threatened by relatively high storm surges, especially during northeasterly storms (Stigge, 1994), due to the shallow basin depths and a highly differentiated coastline.
The western coastal waters of Poland are shallow along the entire coastline. Especially in Zatoka Pomorska (Pomeranian Bight), a large shoal area with depths below 20 m extends far seaward in northerly direction. Shallow waters are also encountered farther to the west. Sea level oscillations of a remarkable range occur frequently at the coasts of such shallow waters.

1.4 Meteorological conditions accompanying high sea levels in 1951 – 1999

Storm surges on the southern Baltic Sea coast are most likely to occur after the passage of a low pressure centre with a system of atmospheric fronts. The most dangerous storms of the 20th century raging along the entire southern coast usually accompanied a stormy depression tracking southeastward from the Norwegian Sea across Scandinavia and the Baltic Sea.
Storm surges are induced by gale-force winds from northwesterly to northeasterly directions, which appear in the rear of such fronts. Storm surges of this type may last from a few hours to tens of hours. When such surges overlap with an already high sea level induced by large inflows from the North Sea, the resulting sea level may be very high, reaching extreme values in some cases. Sometimes the sea level rise begins simultaneously along the entire coastline, but more often the surges strike only part of the coastline or move along the coast. Heavy and long-lasting storms are usually accompanied by a considerable sea level rise along the entire coastline.

2. LONG-TERM VARIATION OF STORM SURGE OCCURRENCE

The long-term variation of storm surge occurrence and annual frequency distribution provides important information on this hydrological phenomenon.

2.1 Gumbel probabilities

Some principles of this statistical method were described by Stigge (1995b). The following table allows a comparison between the levels of flood protection (defence level – generalised mean sea level) and some high water levels of different probabilities of undercut P or intervals of recurrence T in years.

Table 2.1. Some high water levels in m above MSL for Gumbel probabilities of undercut P and intervals of recurrence T in years for German coastal towns calculated in 2000

Gauge/P	0.80	0.90	0.95	0.98	0.99	Defence level
Name / T in years	5	10	20	50	100	
Flensburg	1.45	1.63	1.81	2.04	2.21	3.50
Schleimünde	1.38	1.54	1.70	1.89	2.04	3.70
Eckernförde	1.43	1.63	1.82	2.07	2.25	3.60
Kiel	1.45	1.65	1.84	2.08	2.26	3.40
Neustadt	1.38	1.57	1.75	1.99	2.16	3.30
Travemünde	1.50	1.70	1.89	2.14	2.32	3.70
Wismar	1.49	1.68	1.86	2.09	2.26	3.20
Warnemünde	1.28	1.44	1.60	1.80	1.95	2.85
Stralsund	1.17	1.31	1.45	1.63	1.77	2.70
Greifswald	1.34	1.50	1.65	1.85	2.00	3.00
Świnoujście	1.16	1.31	1.46	1.65	1.80	0.80
Kołobrzeg	1.13	1.26	1.39	1.54	1.66	1.10

The sequence of the gauges is from west to east. The highest levels occur in bights that are open to the northeast.

2.2 Long – term variation of storm surges

Because of the strong frequency fluctuation of surges, a presentation of the highest storm surges requires a compression of the linear time scale. Figure 2.1. shows the maximum water levels of the highest storm surges on a six-month basis (January-July / August-December), observed at the Warnemünde tide gauge between 1870 and 2000.

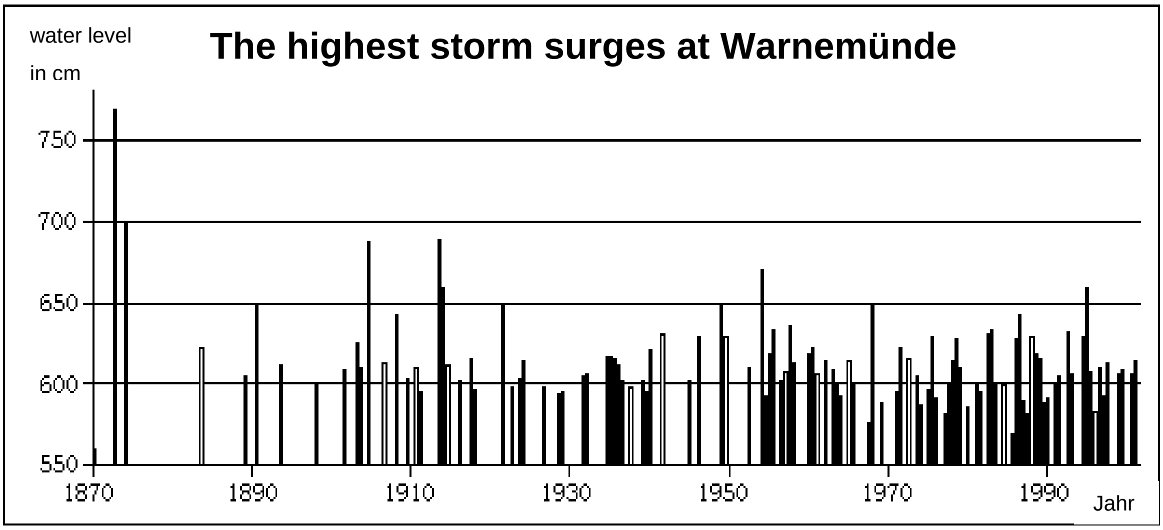

Fig. 2.1. Maximum water levels of the highest storm surges on a six-month basis 1870 - 2000

The gaps during the 19th century are due to missing data. Complete data are available for the 20th century. Verified data for the western part of the coast cover the years 1950 – 2000.
Fig. 2.2 shows the distribution of the number of storm surges during the 1951 – 2000 seasons. Each number is expressed as per cent of the total number of events that occurred in these years. One season covers the period from August of the preceding year to July of the year in question. The mean annual (seasonal) number of storm surges was slightly above 2 in this 50-year period. The highest number of surges, recorded in 1989/90, was as high as 7. Five storm surges were observed in the seasons 1973/74, 1988/89, 1991/92, and 1997/98. As many as 8 seasons were free of surges (1956/57, 1965/66, 1966/67, 1968/69, 1969/70, 1984/85, 1987/88, and 1990/91).

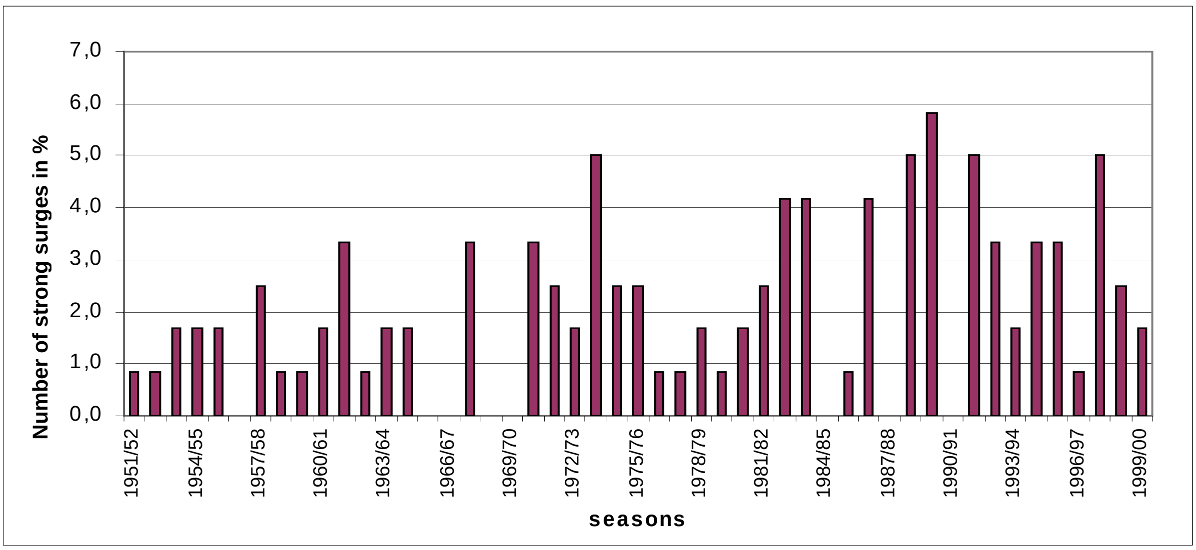

Fig. 2.2. Number of storm surges recorded in particular seasons in Świnoujście from 1950 to 2000; in % of the total number of events that occurred in the second half of the 20th century

The probability of storm surge occurrence was highest in the 1970s (with at least one storm surge in every season; probability = 100%) and lowest in the 1960s (probability = 60%). From the beginning of the verified observation series, i.e. from 1950/51, the number of surges per decade increased from 13 in the 1950s through 15 and 22 in the two following decades to 34 in the 1980s. A scarcely smaller number of surges, namely 32, was recorded in the last decade of the 20th century. This allows the conclusion that by the end of the century the threat of storm surge flooding had almost doubled as compared to the middle period.

2.3 Monthly frequency distribution of storm surges

Two factors are mainly responsible for the occurrence of a storm surge: a high daily reference sea level on a particular coast and strong, usually gale-force, onshore winds. Gale-force conditions are most frequent during the cold season from November (sometimes August) to February (sometimes April).

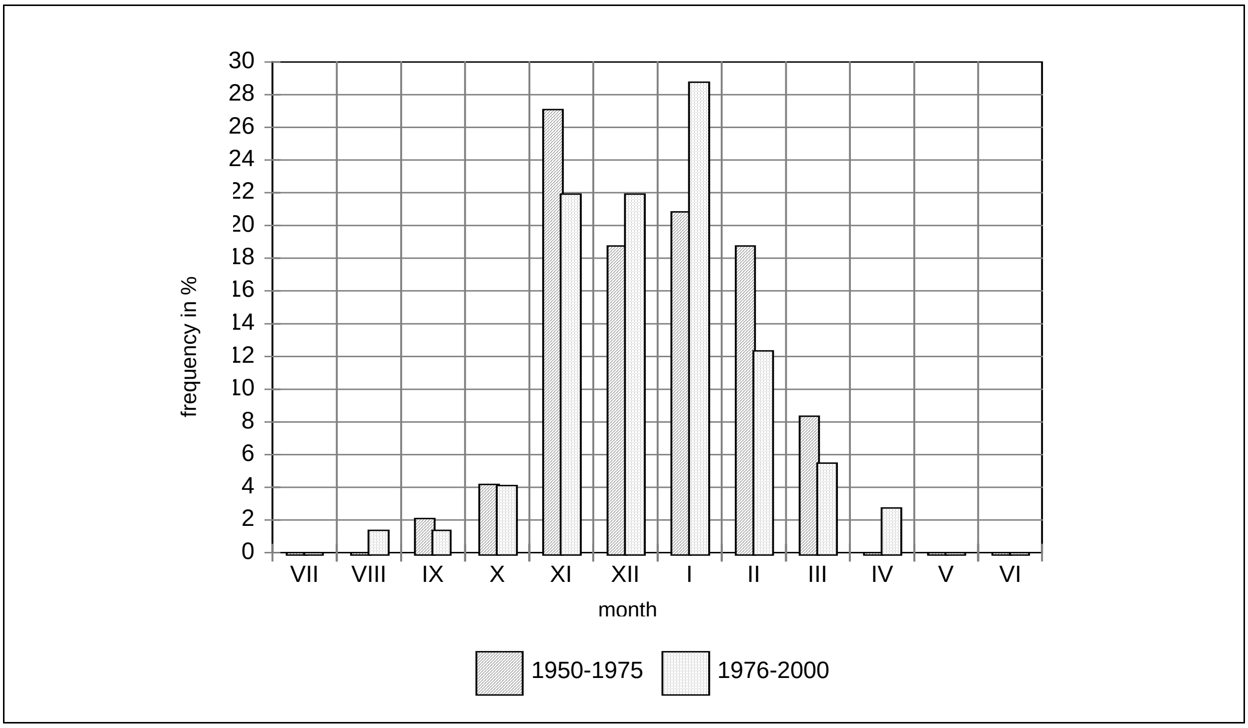

Fig. 2.3. Mean monthly frequency distribution of storm surges in two periods, 1950 – 1975 and 1976 - 2000

In the two periods considered, 1950 – 1975 and 1976 – 2000, the mean annual (seasonal) distributions differ only with respect to the month of maximum occurrence: in the first 25 years, storm surges were most frequent in November (about 27% of events) while the maximum in the 1976 – 2000 period shifted to January, with about 29% of all storm surges. The storm surge seasons in the period from 1950 – 1975 were shorter. The first storms usually occurred as late as September (about 2%), and the last ones in March, with a frequency of 8%. Storm surge seasons in the period from 1976 – 2000 extended from the last days of August (with a frequency of only 1%) to April (about 3% of annual storm surges).
The absence of these phenomena in May, June and July is characteristic of the monthly frequency distribution of storm surges.

3. FEATURES OF STORM SURGES

Some characteristic parameters (calculated for each particular storm surge) define the features of storm surges threatening the coasts and constitute the basis of the storm surge definition provided in chapter 1.

These parameters include the maximum sea level recorded during the surge and the mean daily reference level indicator, which is a highly useful parameter in routine operational forecasting. The latter is determined by the surplus (above the multi-year mean sea level) of surface water accumulated off the southern coast. Other important parameters are the duration (persistence) of the high levels, and the persistence of levels above the warning and alarm levels (560 cm and 580 cm at Swinoujscie).

3.1 Maximum sea levels

The highest sea levels in the area under review were observed during storm surges; the 700 cm level was exceeded at the Wismar station in November 1995, at a level of 702 cm. During the same storm, Świnoujście (661 cm) and Warnemünde (660 cm) reported the highest levels of the 1976-2000 period. By contrast, the highest level in Sassnitz was observed in January 1992, at 636 cm, and in Kołobrzeg in November 1988 (642 cm).

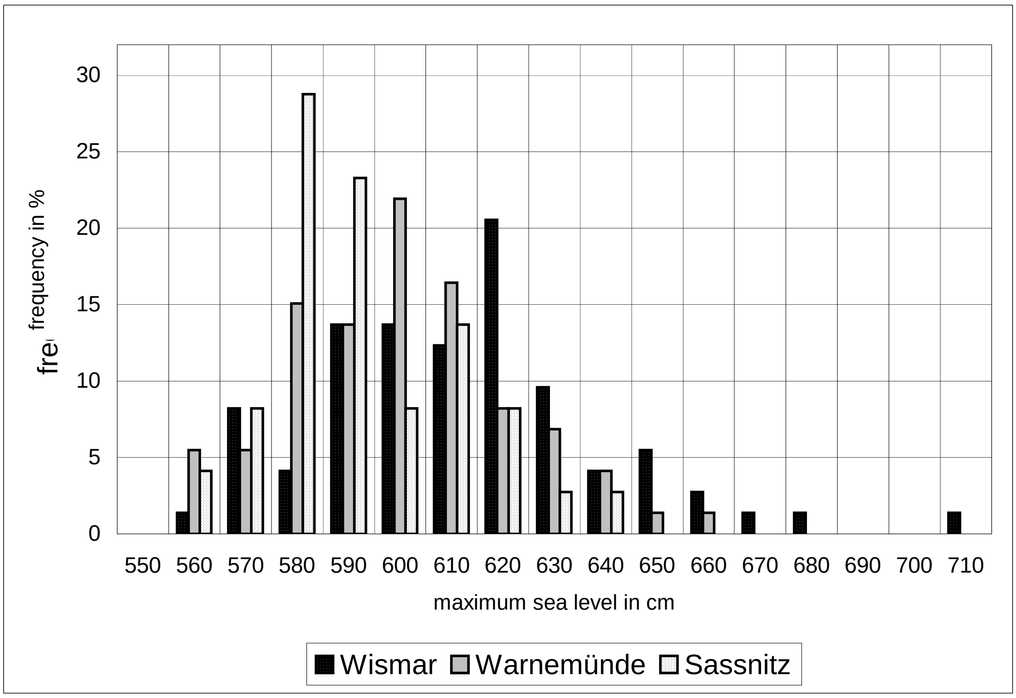

Fig. 3.1. Frequency distribution of maximum sea levels observed during storm surges at Wismar, Warnemünde and Sassnitz in 1976-2000

The frequency distribution of maximum sea levels (analysis of sea levels at the German stations in 1976-2000) is presented in Fig. 3.1. Maximum sea levels (during storm surges) at the Wismar station were observed most frequently (about 20%) in the 610-620 cm range. At Warnemünde, about 21% of maximum levels were within the 590-600 cm range. At Sassnitz, up to 52.1% of the maximum sea levels ranged between 570 and 590 cm.

The frequency distribution of maximum sea levels (reported at Świnoujście and Kołobrzeg during storm surges in 1976-2000) is presented in Figs. 3.2. and 3.3., in comparison with the 1950-1975 period. In both periods, i.e. 1950-1975 and 1976-2000, the maximum sea levels ranged mostly from 570-590 cm; at Świnoujście, the percentage was 48% in the former period and 52% in the latter, compared to about 53% and 49%, respectively, at Kołobrzeg. At

Kołobrzeg, however, there has clearly been a change (from 19% to 30%) in the occurrence of maximum levels - from the 570-580 cm to the 580-590 cm range.

Also an increase in the number of very high storm surges (with maximum levels exceeding 640 cm) was observed at the two above-mentioned Polish stations. At Świnoujście, the number of storm surges with maximum levels of about 570 cm decreased during the last 25 years of the 20th century.

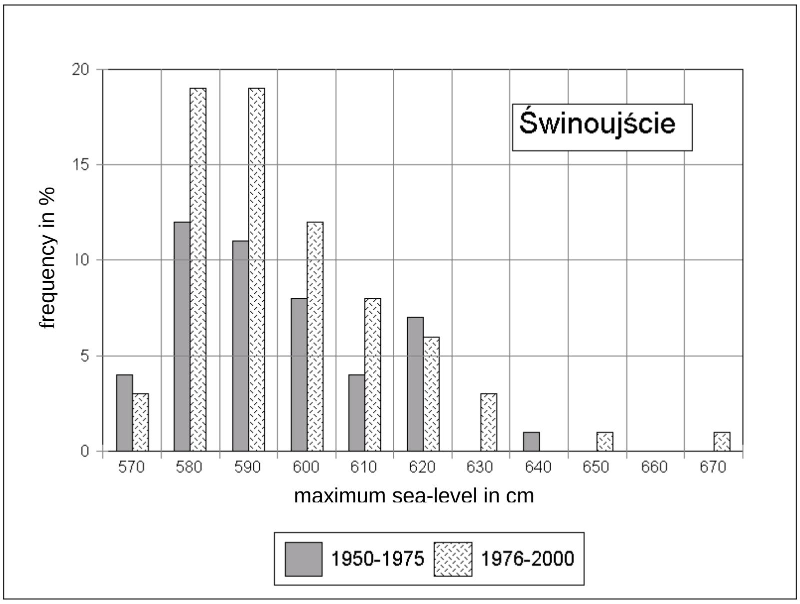

Fig. 3.2. Frequency distribution of maximum sea levels at Swinoujście during storm surges in 1950-1975 and 1976-2000

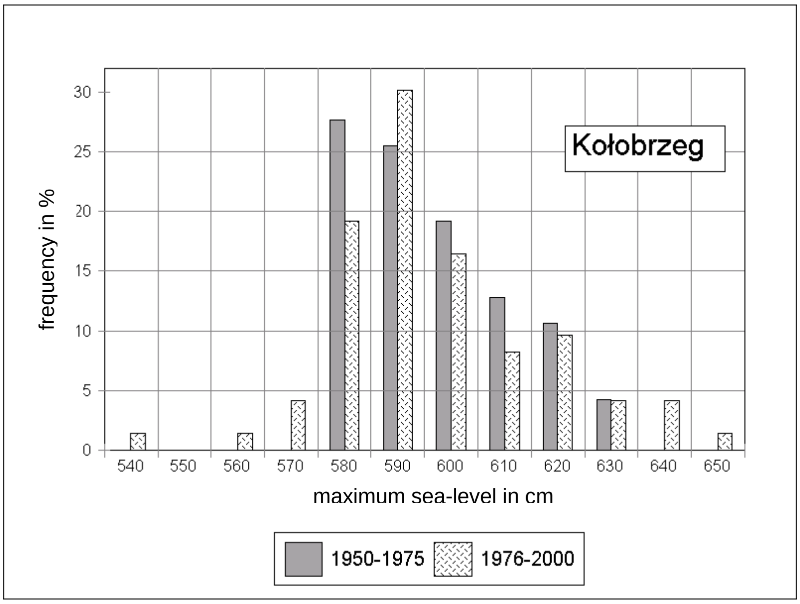

Fig. 3.3. Frequency distribution of maximum sea levels at Kołobrzeg during storm surges in 1950-1975 and 1976-2000

3.2 Daily reference sea level value

This one-dimensional parameter in cm represents the influence of the actual averaged sea level of the whole Baltic Sea on sea level values along the southern coasts. The formula of this parameter is based on the air pressure differences on particular cross-sections of the Baltic Sea, air and surface water temperature differences, wind directions, and on the season (cold, warm). The formula was developed empirically by Maliński at the end of the 1960s. The value of this parameter is calculated daily at the Hydrological Forecasting Office in IMGW Gdynia. Among other purposes, this parameter is used to indicate the beginning of a storm surge. The daily reference sea levels for each storm surge investigated are listed in Table 1.1., and their frequency distribution in Fig. 3.4. An analysis of the maximum and mean values of this parameter (Kowalska,1997) indicates an increase in the mean value in 1980, which was probably due to prevailing westerly air flow during this decade. The maximum values of the daily reference level occurred in the autumn-winter season. During nearly 50% of the surges this parameter was as high as 521 to 550 cm. During 23% of the surges it oscillated between 491 and 520 cm, and a parameter below 490 cm was observed in only 3% of the surges. Low values (below 510 cm) of the daily reference sea level during a storm surge may indicate that the dynamics of the surge was very high, involving in particular a rapid rate of increase of the water levels.. On the other hand, very high values of this parameter (e.g. above 550 cm) even before the maximum may suggest that winds in the vicinity of the tide gauge may not be very strong or there may be no wind at all.
Comparing the two observation periods of 1950-1975 and 1976-2000, one can prove that storm surges in the latter period were more frequent at daily reference level ranges of 511 - 530 and 551 - 560 cm respectively, and at the extreme value of the parameter, i.e. above 560 cm. The value of 555 cm was surpassed in only 5% of all storm surge events.

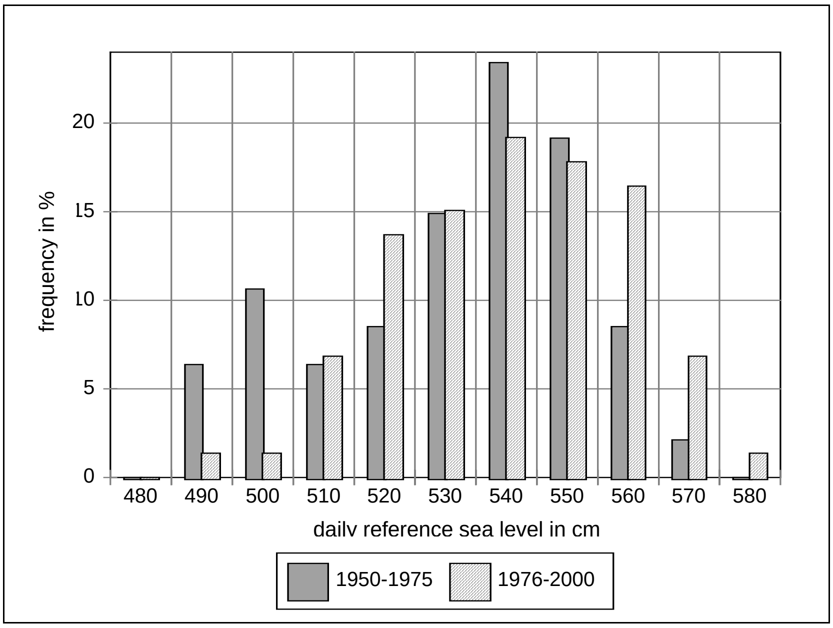

Fig. 3.4. Frequency distribution of the daily reference sea level values in cm on the storm surge days

3.3 Duration of storm surges at Świnoujście

In order to estimate the duration of a storm surge, two points in time have to be determined: its beginning and end. For example, the inflexion point of the tide curve may be used as the beginning of a storm surge. In the forecasting routine in the Baltic Sea, however, this point cannot be predicted in advance (in real time). Therefore, for practical purposes, a daily reference sea level indicator parameter is applied to calculate the duration of a storm surge.
The hour at which the sea level rises above the daily reference sea level (before reaching the maximum value) has been defined as the beginning of a storm surge, and the hour at which it drops below the daily reference sea level (after having reached the maximum value) as its end.
At Świnoujście, surges lasting 21 - 30 hours and 31 - 40 hours had the highest frequency (26% and 25%, respectively), which amounted to about half of all surges. 19.2% of all surges lasted 11 - 20 hours, and about 12% of surges were in the 41 - 50 hour range. Only 10.9% of the surges lasted from 51 to 70 hours, and 6.9% more than 70 hours. The surges with the longest duration on record at Świnoujście in the second half of the 20th century exceeded 80 hours and occurred in April 1997 (117 hours), February 1979 (85 hours), November 1981 (93 hours), and January 1987 (82 hours).

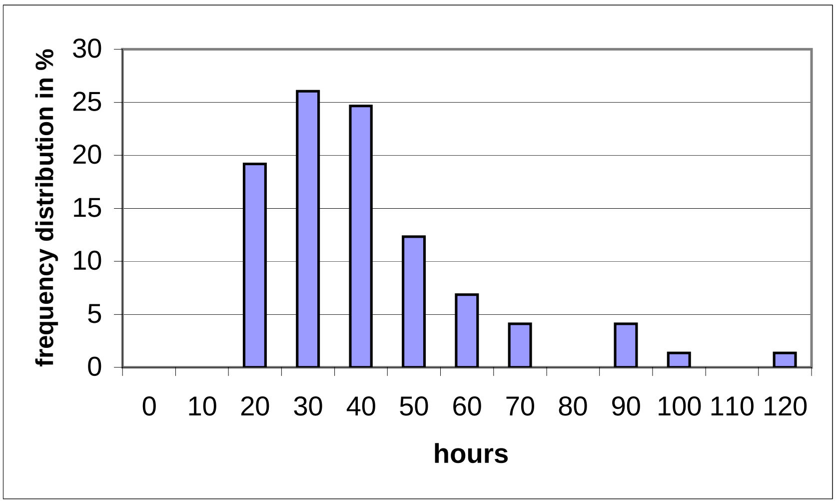

Fig. 3.5. Storm surge duration at Świnoujście - frequency distribution

3.4 Warning and alarm levels

The warning and alarm levels for a particular section of the coast are determined taking into account the height and frequency of occurrence of dangerous surge levels, the configuration of the coastline, and existing coastal defence structures such as dikes etc. In case of an expected storm surge, the hydrological forecasting services are required to inform the responsible authorities of the expected duration of the dangerous surge level above the warning levels, and particularly above the alarm levels. This information is essential for the organisation of protection measures.
At the coasts around Świnoujście, the warning and alarm levels have been set at 560 cm and 580 cm, respectively. Higher levels have been set at the coasts between Sassnitz and Wismar, at 600 cm.
The period during which emergency levels were exceeded is indicated in hours as an annual total of each stormy season (Table 3.4.).

Table 3.4. Number of hours in which water levels reached or exceeded 560 cm or 580 cm in the seasons of 1976-2000

Seasons	Wismar		Warnemünde		Sassnitz		Świnoujście		Kołobrzeg	
	≥560	≥580	≥560	≥580	≥560	≥580	≥560	≥580	≥560	≥580
1975/76	126	39	116	35	98	11	178	36	279	54
1976/77	50	8	39	5	16	2	57	16	22	9
1977/78	79	15	62	11	65	12	81	22	150	28
1978/79	243	155	215	110	106	43	56	0	126	43
1979/80	30	19	27	17	28	1	35	0	23	0
1980/81	127	44	148	26	133	2	206	9	226	22
1981/82	163	62	183	52	198	20	349	81	361	89
1982/83	136	56	140	57	244	74	262	73	347	91
1983/84	145	65	129	60	155	51	149	61	277	56
1984/85	63	28	48	17	16	0	39	6	23	1
1985/86	73	7	48	0	34	0	45	9	64	9
1986/87	258	130	225	102	177	62	177	57	156	35
1987/88	154	54	90	19	24	1	23	0	32	0
1988/89	204	76	142	56	86	28	151	60	188	79
1989/90	231	103	184	70	127	20	232	57	286	84
1990/91	141	19	57	13	24	5	22	7	21	5
1991/92	142	57	94	36	129	27	112	28	196	59
1992/93	94	33	79	29	71	15	219	45	206	61
1993/94	97	31	54	19	50	0	53	0	45	0
1994/95	138	70	109	51	84	28	168	52	193	61
1995/96	200	94	155	69	81	29	128	45	105	47
1996/97	97	32	77	16	36	9	56	13	60	22
1997/98	144	54	124	42	59	3	112	12	166	18
1998/99	66	5	39	0	15	0	39	2	150	19
1999/00	168	61	159	44	81	17	183	33	258	42

The maximum annual (seasonal) totals were recorded in the eastern part in 1981/82: they reached 361 hours at Kołobrzeg, 349 hours at Świnoujście above or equal to the 560 cm. In the western part of the coast, the maximum annual totals were reached in the 1986/87 season: the number of hours with levels exceeding 560 cm was as high as 258 in Wismar, and 225 in Warnemünde. At Sassnitz, the longest duration of sea levels above or equal to 560 cm was recorded in the season of 1982/83 (244 hours).

In the western part of the coast, annual maxima of the total number of hours with levels exceeding 580 cm were observed during the 1978/79 season (at Wismar 155 hours and at Warnemünde 110 hours). 1982/83 was the most dangerous season at Sassnitz (74 hours with sea levels equal to or above 580 cm) and at Kolobrzeg (91 hours with sea levels equal to or above 580 cm).

Only in 4 out of the 25 seasons studied were no hours recorded in which the value of 580 cm was exceeded.

The last 10 years of the past century were rather similar regarding the length of the periods during which defined surge levels were exceeded, both in successive seasons and at particular water gauges, although in the central part of the coast the periods with water levels above the 560 cm level were somewhat longer than in the western part of the southern Baltic Sea coast.

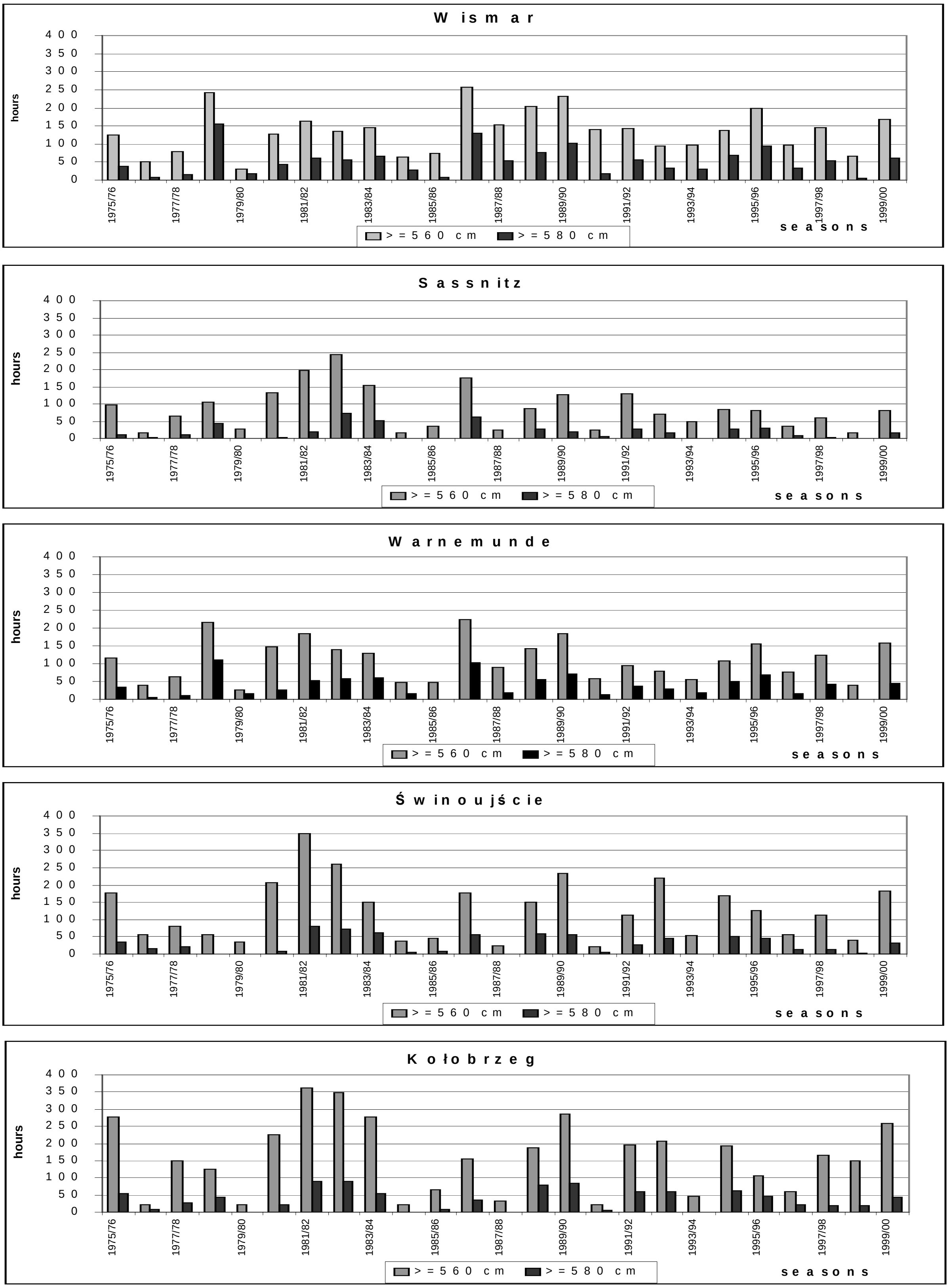

Fig. 3.6. Number of hours during which sea levels reached or exceeded 560 or 580 cm. A stormy season lasts from August of one year to July of the next year.

4. PERIODICAL SEA LEVEL OSCILLATIONS

The German Baltic coast, situated on the western edge of the Baltic length axis, is predestined for relatively high storm surges, especially during northeasterly storms (STIGGE, 1994). Because of the economic relevance of the area, both a system of coastal protection and an operational water level forecasting service are needed. Coastal flood defences on the coasts (e.g. dykes) have been designed on the basis of local surge probabilities. The meteorological conditions causing a storm surge of about 1m on the Pomeranian coast may lead to a storm surge of about 1.5 m on the coast of Schleswig-Holstein. This has been taken into account in the historic development of coastal defences. Therefore, the dykes in the eastern parts are mostly lower than in the western parts of the German Baltic coast. Extreme sea level oscillations result not only from weather influences but also from seiches of the entire Baltic system (with periods of 27.5 - 39 hours) or from oscillations of bights or estuaries having characteristic periods of a few hours. Fig. 4.1. shows a water level oscillation of about 3 m per 24 hours at the tide gauge at Kiel-Holtenau. The oscillation was influenced by a change of wind direction from north-east to south-west in the Baltic Proper. Fig. 4.2. shows water level oscillations of about half a metre per hour in the Warnow estuary at Rostock.

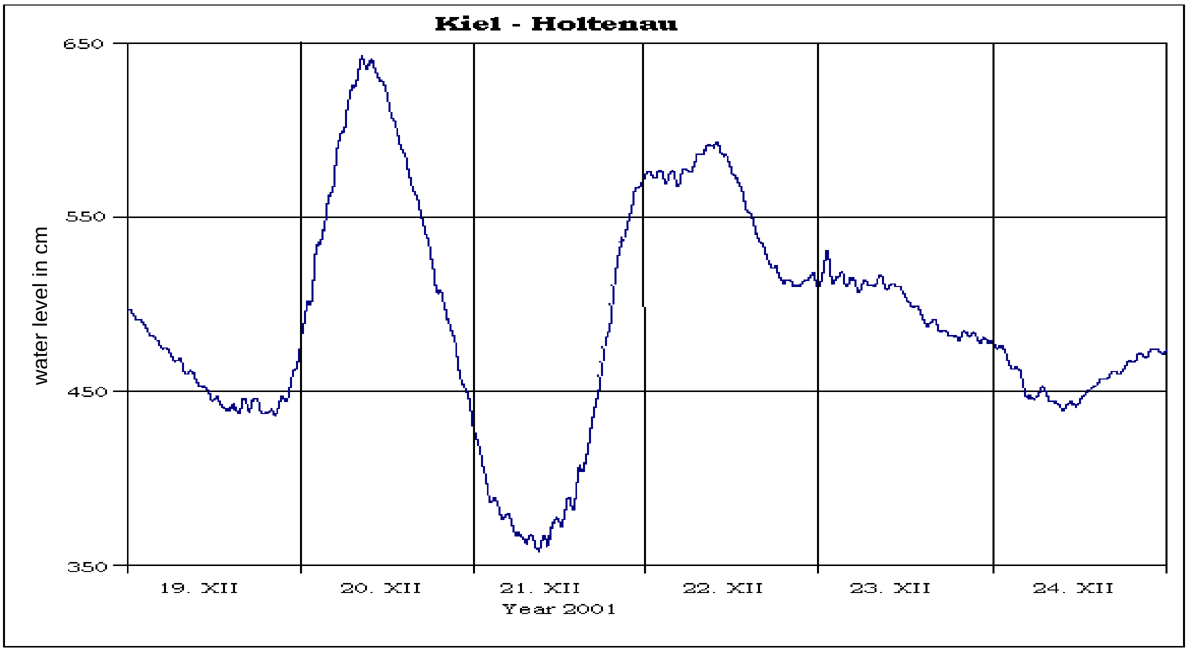

Fig. 4.1. Water level oscillation of about 3 m in 24 hours at the tide gauge Kiel-Holtenau, influenced by a change of wind direction in the Baltic Proper.

Especially the westernmost parts are influenced by regular tides having periods of 12.4 hours and amplitudes of about 15 cm at Wismar (Fig. 4.3.), and 10 cm at Warnemünde. Therefore, storm surges with a duration of mostly about 1 or 2 days may be modified by different kinds of oscillation.
Other periodic sea level changes that have been observed have periods of 1 1/2 years, with resulting elevations of about 20 cm. The mean sea level (of, e.g., one week) without any storm-induced elevation is a measure of the so-called 'degree of filling' (of the whole Baltic sea). Sea levels rise when low pressure troughs travel across Scandinavia from south-west to north-east, and such situations may persist for several weeks. During such weather situations strong south-westerly winds occur in the Baltic Proper, westerly winds in the western Baltic, and north-westerly winds in the Kattegat. This leads to a permanent inflow of water masses from Kattegat to the western Baltic. Last but not least, also local winds may modify storm surges, as has been described by Stigge (1995).

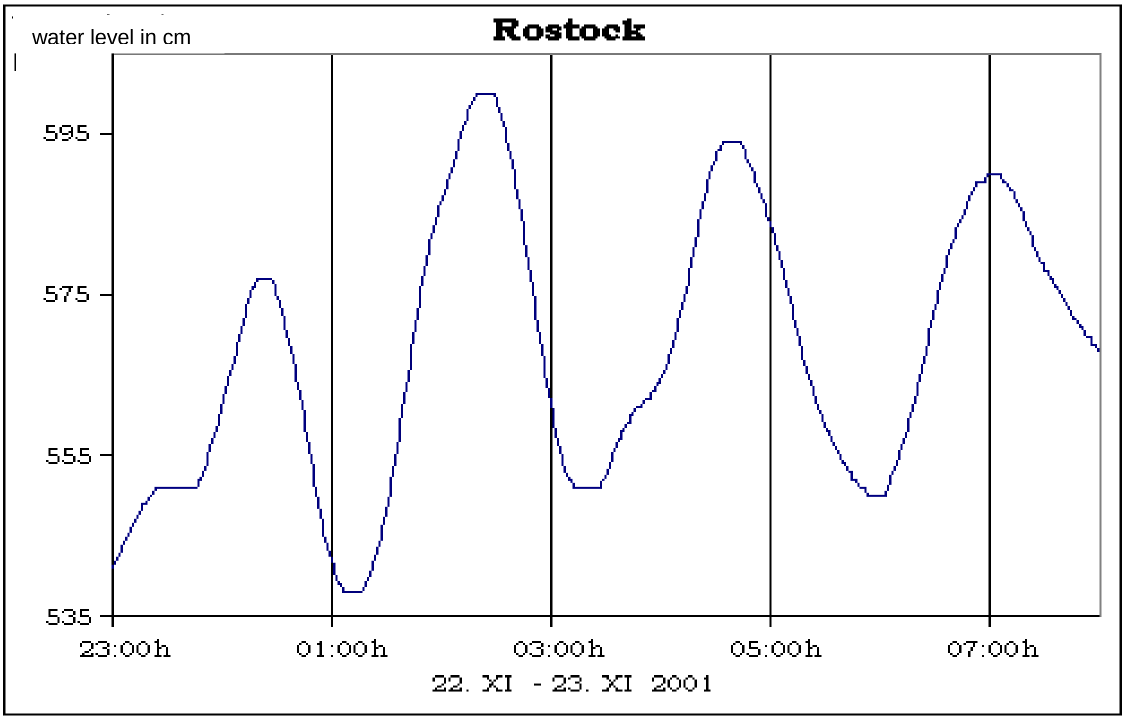

Fig. 4.2. Water level oscillations of about 0.5 m / h in the Warnow estuary at Rostock

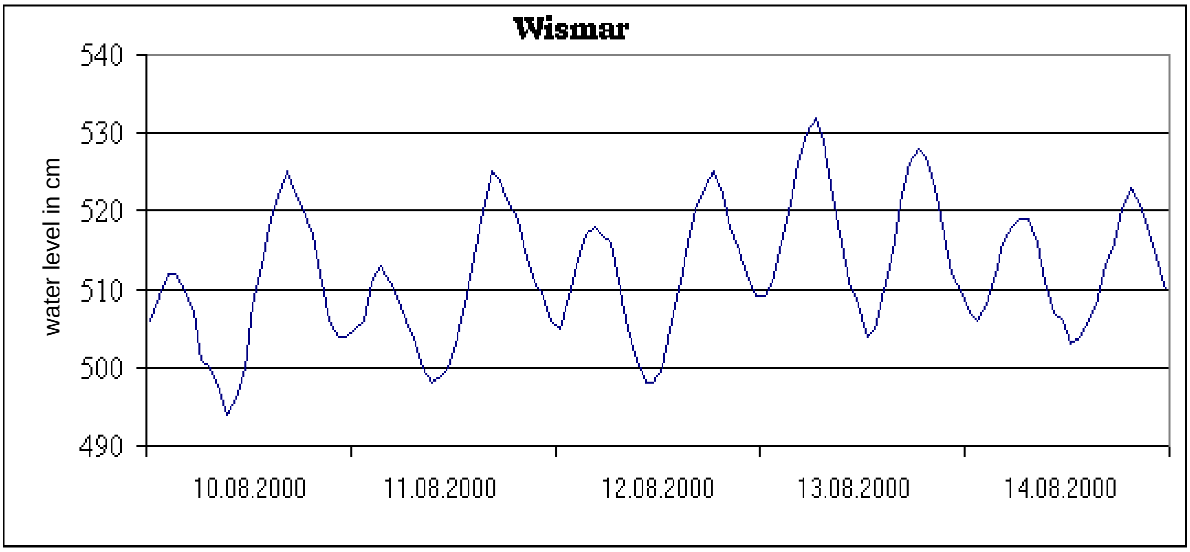

Fig. 4.3. Example of regular semidiurnal tides at the Wismar gauge from 10-14 August 2000

As has been pointed out above, the westernmost basins of the Baltic Sea have clearly distinguishable tides. Their amplitude reaches about 15 cm and diminishes toward the east. Tides in the central part of the Baltic Sea are negligibly small, and their amplitude hardly reaches 3-5 cm. It has been assumed that these oscillations are caused by the North Sea tides.

5. TYPES OF ATMOSPHERIC PRESSURE PATTERNS AND WIND FIELDS INDUCING STORM SURGES

As in all semi-enclosed, nearly tideless marginal seas, oscillations of coastal water levels are caused mainly by the impact of strong winds on the surface water (Wielbinska 1964, Malicki, Wielbinska 1992, Sztobryn et al. 1995, 2001, Stanislawczyk 2002). The wind accompanies an atmospheric disturbance moving across the sea or in its vicinity. During onshore winds, the sea level rises due to wind set-up, while strong offshore winds cause a considerable lowering of coastal sea levels. In an area that is influenced by an active atmospheric system, e.g. a low-pressure system with a small radius, wind field directions in front of the system and in its rear may be diametrically opposed. When such a depression is moving along a particular coast, two different coastal sections - sometimes less than a hundred kilometers apart – may simultaneously suffer the impact of stormy winds from opposite directions. The zone of such sharp wind shear, usually along an occluded front, moves along with the advancing depression. Other types of pressure pattern produce stormy wind fields in which the wind directions change less rapidly.

The southern coastal waters of the Baltic Sea are mostly exposed to direct wind set-up caused by stormy winds from the W-NW to E-NE sector although, depending on local morphometric conditions, other directions must be taken into account as well. The western sections of this coast are more sensitive to sea level oscillations than the areas east of the Odra estuary.

In this monograph, only the sea level wind set-ups between Wismar and Kołobrzeg in the years 1976-2000 have been considered. During this period, 73 storm surges in this coastal area were classified as wind set-up surges. In 17 of these surges, at least one of the water gauges indicated a culmination of 600 cm or higher. All of the surges studied were caused by gale-force onshore winds of shorter or longer duration, with a prevailing northerly component of the wind direction. Several types of pressure pattern were identified that had caused these winds.

5.1 <u>Northerly air flow over Scandinavia and the Baltic Sea</u>

When an anticyclone located above the British Isles spreads towards Scandinavia and tends to track farther east, low pressure centres travel southwards along a route leading from the extreme northeast of Scandinavia along Finland towards western Russia. The pressure gradient over the Baltic Sea becomes steeper, and the northerly air flow gradually increases in force and gustiness. During the development of this pressure pattern, there are temporary fluctuations of the wind speed resulting from alternating pulsations of the pressure gradient on the edge of developing anticyclones. Besides, disturbances develop in the form of secondary cold fronts in the intensive inflow of air. They tend to deform the uniform air flow: northerly winds preceding the front briefly back NW – W, sometimes even SW, and veer N again behind the front.

With the above pressure pattern, winds usually reach gale force when northerly directions have been established in the whole area, exposing the entire southern Baltic coast to a strong onshore storm with resulting wind set-up. All water gauges normally indicate a gradual increase of sea level, though oscillations are probable.

Examples of this pattern are the storm surges of 11 April 1997 and 17-18 January 2000.

Deviations from the above pressure pattern occur when depressions travel southeast across the Baltic Sea or across land along the Baltic east coast towards the Russian plains, with a high-pressure ridge developing over Scandinavia after their passage. This pressure pattern is characterised by cyclonic veering of winds over the Baltic Sea and the adjacent coast in the initial phase. In front of the advancing depression, winds veer SE - SW in a rather large area, increasing in force before the frontal line that is usually connected with the low pressure centre. Such frontal winds veer rather sharply NW, N, and temporarily even NE. The whole system moves S-SE, with an intensive northerly air flow at the rear of the depression, and soon covers the entire area of the Baltic Sea. This phase of the storm surge,

when the northerly onshore storm strikes the southern coastal waters, marks the beginning of the wind set-up. This phase is sometimes preceded by a temporary lowering of sea levels due to strong alongshore to offshore prefrontal winds.
Storm surges generated by the above meteorological pattern were, e.g., the wind set-up on 25-26 December 1976, 29-30 November 1988, 1-4 January 1995, and 3-4 November 1995.

5.2 Stormy low pressure centre moving across the Baltic Sea

A rather large proportion of the low-pressure systems generating storm surges and wind set-up at the southern Baltic coasts track across the Baltic Sea between approximately 60º N and the southern coast. While such low-pressure centres cross the Baltic basin, they are preceded by offshore winds on the southern coasts, and as they move eastwards, onshore winds follow in their rear. The rather regular, circular wind distribution around the storm centre is usually modified by a system of atmospheric fronts which is connected with the centre. Depending on the track of the low-pressure centre - across southern Sweden, across the southern basins of the Baltic Sea or across land along the southern coasts – its passage has different effects on the different coastal sections.

a) With a low-pressure centre travelling across southern Sweden, the southern Baltic coasts come under the influence of southerly winds. Very strong winds, which are frequent in this area, may initially lead to rapidly falling sea levels. Winds on the southern Baltic coasts will only veer onshore when the depression has moved farther east and the atmospheric front has crossed the coastline. The change to N – NE wind directions may be very sharp, with an immediate and violent impact on the coastal waters. In the western parts of the coast, the increase in wind speed begins earlier and the wind setup occurs earlier (by a few hours) than farther east.
b) With a low-pressure centre travelling across the southern basins, SW – SE winds prevail initially in the coastal zone. This may be followed by a brief calm after which NE winds increase rapidly to gale force and, veering SE – SW, may develop into a strong westerly (alongshore) storm lasting several hours, after which the winds veer sharply NE – N. In the event of the atmospheric front (the shift line of wind directions) overlying the coastline, the sequence of wind directions, and hence of the different storm surge phases, may deviate from the normal pattern. Also sea levels may culminate or fall later than usual.
c) With a low-pressure centre moving across land close to the southern coast, the fetch of strong SE – SW winds does not extend across the coastal waters, and the SE – E winds in front of the depression influence only a limited area over the southeastern basins, causing water levels to sink rather slowly or not at all. At the rear of the depression, a NE – N storm causes sea levels to rise rather rapidly, starting in the western parts of the coast. As the depression advances east, all sections of the southern coast are affected successively by the storm surge. However, the culmination of wind setup on the eastern coasts may occur several hours later than in the west.

5.3 Storms from the eastern sector

Storms from the eastern sector (E - NE wind directions) pose a particular threat to the western basins of the Baltic Sea.

a) With a stable high-pressure system over Scandinavia, often the ridge of an anticyclone from northern Russia, an easterly air flow passes across the southern basins. When a depression approaches from southeastern Europe or Poland, a steep pressure gradient forms along the southern or southeastern edge of the anticyclone. A SE – NE storm of rather long duration develops over the southern part of the Baltic Sea because the anticyclonic pressure pattern over northeastern Europe often has a quasi-stationary character. This wind pattern leads to a gradually rising sea level which reaches high values in the westernmost part of the southern basins, e.g. in the Bights of Mecklenburg and Wismar, which are open towards the northeast. An example of this anticyclonic pressure pattern over Scandinavia with an eastward extension was the meteorological situation on 12 January 1987, which resulted in a long-lasting E storm and rising sea levels, which reached 673 cm at the Wismar gauge. The wind setup was much less pronounced in the central parts of the coast and farther to the east.

   There are some easterly weather patterns, especially those in which the high-pressure zone over Scandinavia does not extend far to the east, in which only a rather small area of the southern Baltic Sea is affected by the wind field of the depression approaching from the southeast. A storm from N – NW directions developing as the depression approaches influences primarily the eastern and central parts of the coast, causing sea levels to rise only in these areas, e.g. on 29 November 1978, 18 January 1981 and 6 September 1992.

   The above grouping of typical pressure patterns is not meant to be a classification of meteorological situations based on the similarity of their impact on sea levels along the southern Baltic coast. Such groups cannot be precisely defined because meteorological conditions in the area are continually changing, and it is impossible to find two identical pressure patterns even in an area as limited in extent as the Baltic Sea. Summarising the above, it can be said that, irrespective of the direction of the approaching depression and the prevailing pressure pattern, the response of sea levels in a particular section of the coast depends on its morphometric conditions and the resulting impact of the wind on the near-shore coastal waters. Any type of onshore wind may lead to a considerable rise of sea levels on the coast, provided it is strong enough and has a long fetch, both of which are factors extending the duration of the storm. The problem is to determine the threshold values of these factors.

b) In some other stormy “easterly” situations, especially when the high-pressure zone over Scandinavia does not extend far eastward, the wind fields of depressions travelling northwards from the southeast or southwest may influence a rather limited area of the southern Baltic Sea. A NE – NW storm developing during the approach of a depression of this type usually does not extend farther west than the central coastal area, with sea levels in most cases rising only in these coastal sections. Storm events of this type occurred on 29 November 1978, 18 January 1981, and 6 September 1992.

5.4 Conclusions

The above grouping of typical pressure patterns is not meant to be a classification of meteorological situations based on the similarity of their impact on sea levels along the southern Baltic coast. Such groups cannot be precisely defined because meteorological conditions in the area are continually changing, and it would be impossible to find two identical pressure patterns even in an area as limited in extent as the Baltic Sea. Therefore, also the frequency of occurrence of storm events of a particular group can only be roughly estimated. During the 25-year period studied, about 40 percent of all storm surge events were caused by strong northerly air flow over the Baltic Sea, with high – or rising – atmospheric pressure over Scandinavia and a depression moving southwards near the eastern boundary of the Baltic Sea (type 6.2.1.). About 55 percent of the storm surges were caused by gale-force winds developing at the rear of atmospheric depressions moving eastwards across southern Sweden, the southern basins of the Baltic Sea, or across land close to the southern coast (type 6.2.2.). Only about 5 percent of all storm surge events analysed were due to a strong E air flow over the southern Baltic Sea along the southern edge of an anticyclone over northern Russia and Scandinavia. During some of the easterly storm surge situations, cyclonic circulation was caused by a depression over the mainland which was slowly travelling northwards and encountered blocking high pressure over the Baltic Sea.

Summarising the above, it should be noted that - irrespective of the path of an approaching depression posing a storm surge threat - sea levels in a particular section of the coast react primarily to the impact of the wind on the near-shore coastal waters and depend strongly on the local morphometric and hydrological conditions. Any type of onshore wind may lead to a considerable rise of coastal sea levels if it is strong enough and has a long fetch, both of which are factors extending the duration of the storm. The problem is the determination of the threshold values for these factors.

6. THE MOST DANGEROUS STORM SURGES IN 1976-2000

According to the criteria defined in the preceding chapters, 73 of the flood events in 1976-2000 qualified as storm surges. The meteorological conditions and sea level variations during the most dangerous 17 events have been analysed and described in the following.

6.1 January 1976

Meteorological situation

On 2 January, 1976, the Baltic Sea was under the influence of a high-pressure ridge over western Europe. Westerly winds, which were locally moderate to strong, prevailed along the southern coast. When an active depression, which deepened rapidly on its way east, crossed Scotland between 15 and 21 UTC that day, winds over the western and southern Baltic Sea backed southeast and gradually reached gale force. Soon after the depression (966 hPa at its centre) had approached Denmark at about 00 UTC on 3 January, the southeasterly storm increased to 9 Bft over the Danish Sounds and 7-8 Bft over the western Baltic Sea. As the depression progressed east between 03 and 15 UTC, its abnormally elongated "eye" stretched from Denmark to the Gulf of Gdańsk, tending to form small secondary centres along the occluded front running parallel to the southern coast, which produced a line of sharp wind shear. South of this line, over the southern basins of the western Baltic Sea, the westerly storm spread eastwards (7-8 and 9 Bft). At about 15 UTC, the southern coastal waters were fully under the impact of this storm. North of the wind shear line (occluded front) and closer to the Swedish coast, the storm of 8-9 Bft came from easterly directions, backing northeast and northwest over the Kattegat and Danish Sounds (Fig. 6.1.1.).
Late on 3 January, the depression, while filling, moved slowly southeastward across Poland. Consequently, the entire western and southern Baltic Sea came under the northeasterly to northerly storm of 7-9 Bft, which backed and decreased slightly until the late hours of 4 January. On 5 January at midnight, winds were already backing southwest and south in the western Baltic Sea when another low-pressure trough with gale-force winds approached from the Norwegian Sea.

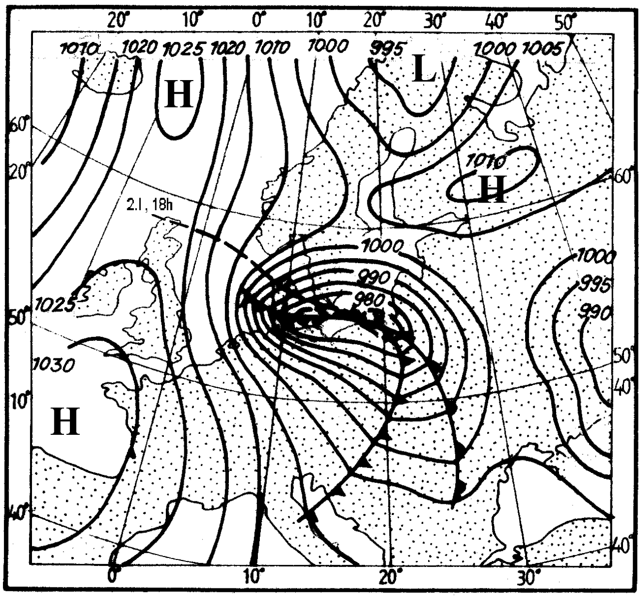

Fig. 6.1.1. Route of the stormy low-pressure centre, pressure pattern over the southern Baltic Sea on 2 January 1976 at 06 UTC

Hydrological response of the sea level

Until about noon on 2 January, the effect of the slightly onshore westerly gale is reflected in a moderate increase of sea levels along the western and central coasts. In the early afternoon, levels begin to decrease, accelerated by the southeasterly gale in the field of the depression approaching from Scotland and the North Sea. Minimum values were reached early on 3 January (Wismar 478 cm, and Warnemünde 488 cm at 02 UTC, Sassnitz about 520 cm between 02 and 03 UTC, Świnoujście 484 cm, and Kołobrzeg 503 cm between 04 and 05 UTC).
The sea level rise that followed was rapid and began as soon as the winds had veered to westerly directions following the passage of the warm front: between 01 - 02 UTC at the western gauges and 04 - 05 UTC in the central part of the coast. Sea levels at the western coast continued to rise until 09 – 10 UTC when, before the passage of one of the secondary centres, winds backed sharply for a short period of time and pushed the surface waters in offshore direction. Sea levels fell to about 500 cm at 14 UTC in Wismar. However, at the same time around midday, levels continued to rise in the central section of the coast and farther east, ceasing only after 13 UTC when the small secondary low reached this area and caused the wind to back offshore. This resulted in a sharp, though insignificant, drop of sea levels in that area: to 552 cm in Świnoujście and 564 cm in Kołobrzeg between 17 and 19 UTC.

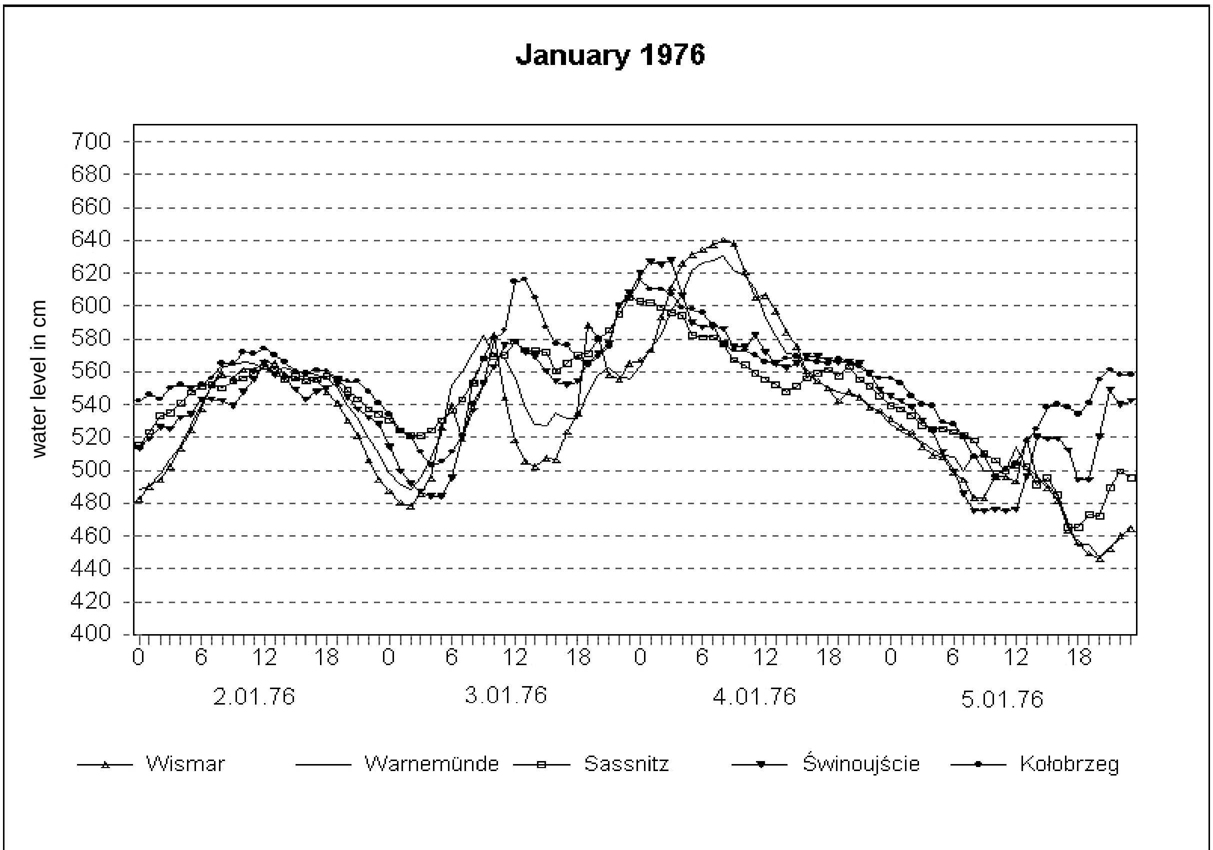

Fig. 6.1.2. Sea level changes during the storm surge of January 1976

These minor sea level oscillations of short duration developed into the main phase of the surge when the gusty NE to NW storm hit the coast directly after the occluded front had crossed the shore line in southeasterly direction. In the central coastal area, the rise of sea levels was smaller and of shorter duration: the culmination began at about 00 UTC on 4 January, with maxima of 616 cm in Kołobrzeg and 628 cm in Świnoujście. When the northwesterly wind backed and decreased slightly after about 04 UTC, water levels fell slowly. The highest levels on the western coast were recorded between 04 and 09 UTC, with maxima ranging between 630 cm in Warnemünde and 640 cm in Wismar, at 08 UTC. Levels then began to fall nearly immediately, which continued until the late morning hours of 5 January. Relative to the reference level indicator (equal to 548 cm on 3 January) this surge lasted between 23 hours at Wismar and 41 hours at Kołobrzeg.

6.2 December 1976

Meteorological situation

On 24 December 1976, after a deep and extensive trough of low pressure had travelled across the Baltic Sea towards Bielorussia and Ukraine, a northerly storm of 7-8 Bft with gusts of 9 Bft set in affecting the entire Baltic Sea from the Gulf of Bothnia to the southern coasts. On 25 December at 00 UTC, another low-pressure centre of 1007 hPa formed over the Norwegian Sea and, steadily deepening, moved rapidly S-SE and later SE. It entered the southeastern basins of the Baltic Sea on 26 December at 00 UTC with a pressure of 987 hPa, slowing down and continuing towards Lithuania, where 985 hPa was recorded on 26 December at 03 UTC. The slowly filling depression then travelled towards Ukraine (Fig. 6.2.1.).

The passage of this low-pressure centre disturbed the existing strong northerly air flow, causing a temporary decrease of wind speed and changes of wind direction along its path, with a spell of strong southerly winds in the night from 25 to 26 December in the entire southern Baltic Sea. However, when a high pressure ridge developed over Scandinavia and the low-pressure centre reached the Lithuanian coast on 26 December at 03 UTC, the whole area of the Baltic Sea was again hit by a northerly storm of 7-9 Bft.

On 26 December, after 15 UTC, as the low-pressure centre moved towards Ukraine and the ridge of high pressure over Scandinavia weakened and slowly spread across the Baltic Sea, the wind finally backed and calmed gradually to 8-5 Bft. On 27 December, the wind continued to decrease, backing west to southwest.

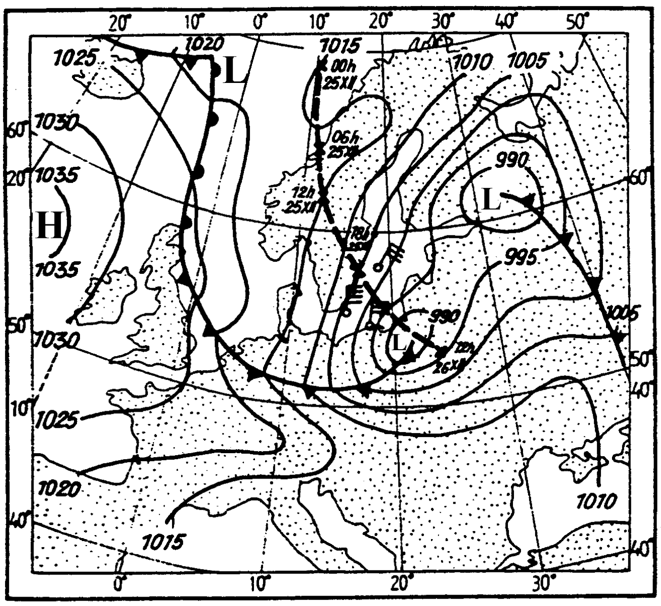

Fig. 6.2.1. Track of the depression, pressure pattern and wind field that caused the storm surge of 24 – 27 December, 1976, on the coasts of the southern Baltic Sea

Hydrological response of sea levels along the coasts

The first phase of the surge began on 24 December around midday. Sea levels rose gradually by an average 6 cm per hour along the entire coast. Maxima in the central part of the coast were reached on 25 December, between 2 and 3 UTC, with values of 562 cm in Kołobrzeg, 580 cm in Świnoujście, and 561 cm in Sassnitz, whereas in the western parts of the coast the culmination was observed between 6 and 7 UTC, with values of 582 cm in Warnemünde, and 590 cm in Wismar. For 12 to 14 hours, sea levels on the entire coast remained 0.7-1.3 m above normal, with a much steeper rise in the western areas.
In the night of 25 December, the impact of strong southerly and southwesterly winds with the resultant cyclonic disturbance caused falling water levels on the shores of the southern Baltic Sea, leading to relatively low water levels in the night from 25 to 26 December (levels ranging from 497 cm in Kołobrzeg to 445 cm in Wismar).

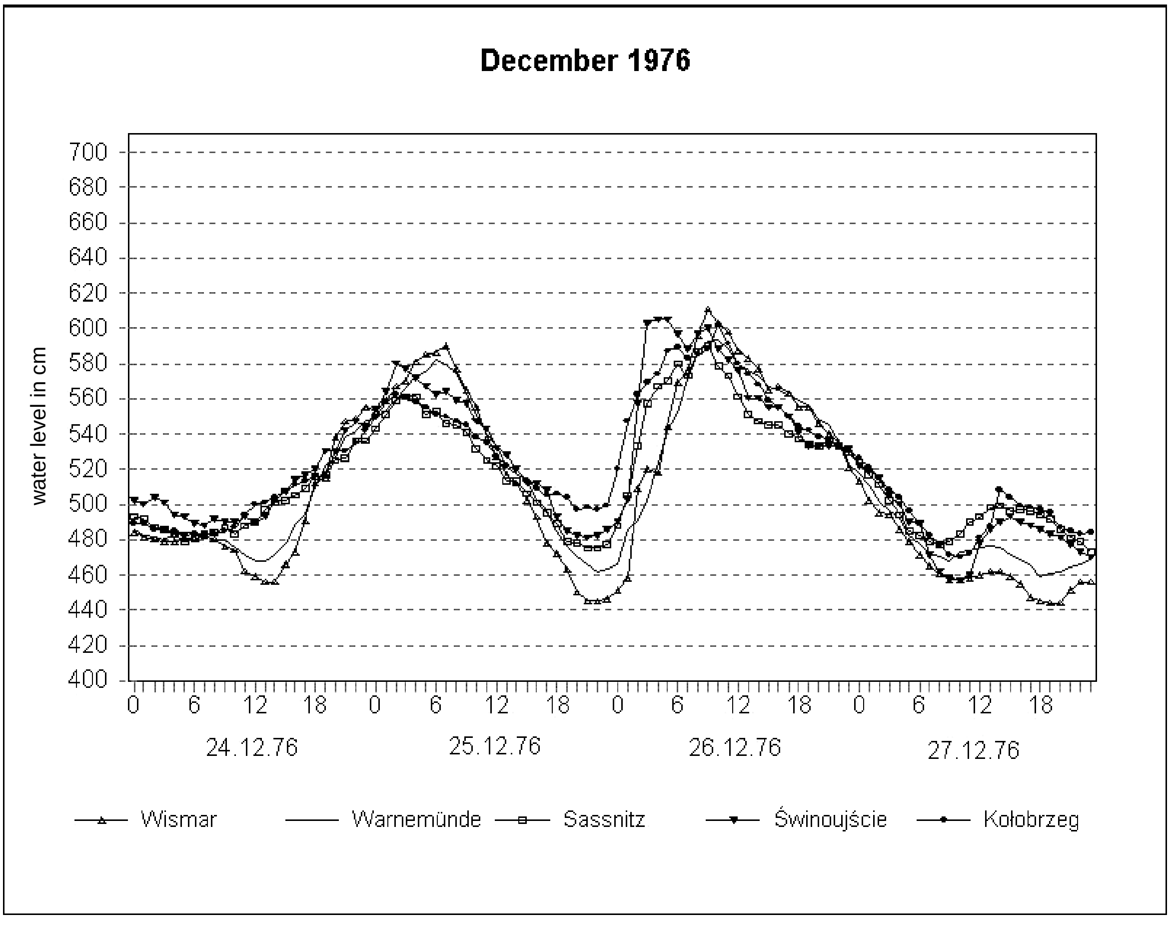

Fig. 6.2.2. Sea level changes during the storm surge of December 1976

An intensive northerly storm in the early hours of 26 December again caused water levels to rise sharply. Maxima were reached at about 10 UTC: 611 cm in Wismar, 593 cm in Warnemünde, 590 cm in Sassnitz, 605 cm in Świnoujście, and 602 cm in Kołobrzeg. In Świnoujście, a local maximum of 605 cm at 4 UTC preceded the general culmination by about 5 hours (Fig. 6.2.2.).
The rise of water levels was very sharp – in just a few hours the water rose by about 1 m in the central part of the coast, and about 1.5 m in its western part. The maximum increase in the culmination phase of the surge exceeded 50 cm per hour. The mean rate of increase ranged from 23 cm per hour in Świnoujście to 11 cm per hour in Sassnitz. The duration of the

surge in relation to the reference level indicator (490 cm on 24 December) ranged from 50 hours in Wismar to 66 hours in Kołobrzeg.

6.3 January 1978

Meteorological situation

On 2 January, a large depression with its centre over the Norwegian Sea extended nearly across the whole Europe. At the edges of this depression, a secondary low pressure centre with 994 hPa began to form on 3 January, at 00 UTC, east of Scotland and soon started travelling southeastward. Within one day, this secondary low covered the area extending from the North Sea across Denmark and southern Sweden to the southeastern Baltic Sea, with its pressure now 12 hPa lower. Behind the depression, a ridge of high pressure spread from the British Isles across the North Sea and Scandinavia.
On 3 January, due to the path of the storm centre which produced a cyclonic wind system in the depression, strong westerly, southwesterly and partly southeasterly gale-force winds of 7-8 Bft developed over the western and central coastal zone and lasted until the early afternoon of 3 January. As the depression moved east and the cold front, progressing southward, crossed the coast, the southwesterly storm veered sharply northwest and north, reaching 7-9 Bft on average, with gusts of 10 Bft. The depression reached the coast of southwestern Lithuania in the morning of 4 January. Its path soon veered and, at about noon on 4 January, the centre began filling as it continued tracking northeast. However, due to the steep pressure gradient over the Baltic Sea, the storm did not decrease until the early hours of 5 January.

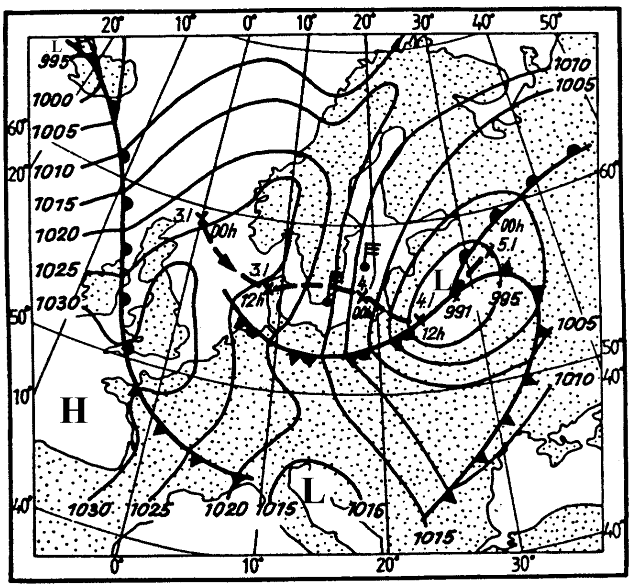

Fig. 6.3.1. Route of the stormy depression from 3 January 1978, 00 UTC, to 5 January 1978, 00 UTC; pressure pattern and wind field over the Baltic Sea on 4 January, 18 UTC

Hydrological response of the sea level

Strong offshore winds on 3 January forced the water away from the shores, causing sea levels to fall considerably below their mean levels (436 cm in Wismar, 16 UTC, and 453 cm in Warnemünde, 14 UTC; only slightly below 500 cm in the central part of the coast, between 08 and 17 UTC). When winds veered onshore, developing into a NW to N storm, a long persistent surge began on the southern coasts of the Baltic Sea. The sea level rise was rapid in its initial phase, with a maximum rate of 61 cm/h in Wismar, 43 cm/h in Warnemünde, and 24 cm/h in Świnoujście. Then, for about 12 hours, water levels rose more slowly and

remained within the warning range until, on 4 January, they culminated around midday in the central parts of the coast, and between 19 and 22 UTC in the western part of the coast.
The maximum sea levels recorded during this surge were 620 cm in Wismar, 602 cm in Warnemünde and Kołobrzeg, 591 cm in Sassnitz, and 583 cm in Świnoujście. Warning levels (above 560 cm) persisted for 31 hours in Kołobrzeg, 22 hours in Świnoujście, and 15 hours in Wismar and Warnemünde.
Relative to the reference level indicator (523 cm on 3 January), this surge lasted from 31 hours in Wismar to 42 hours in Kołobrzeg.

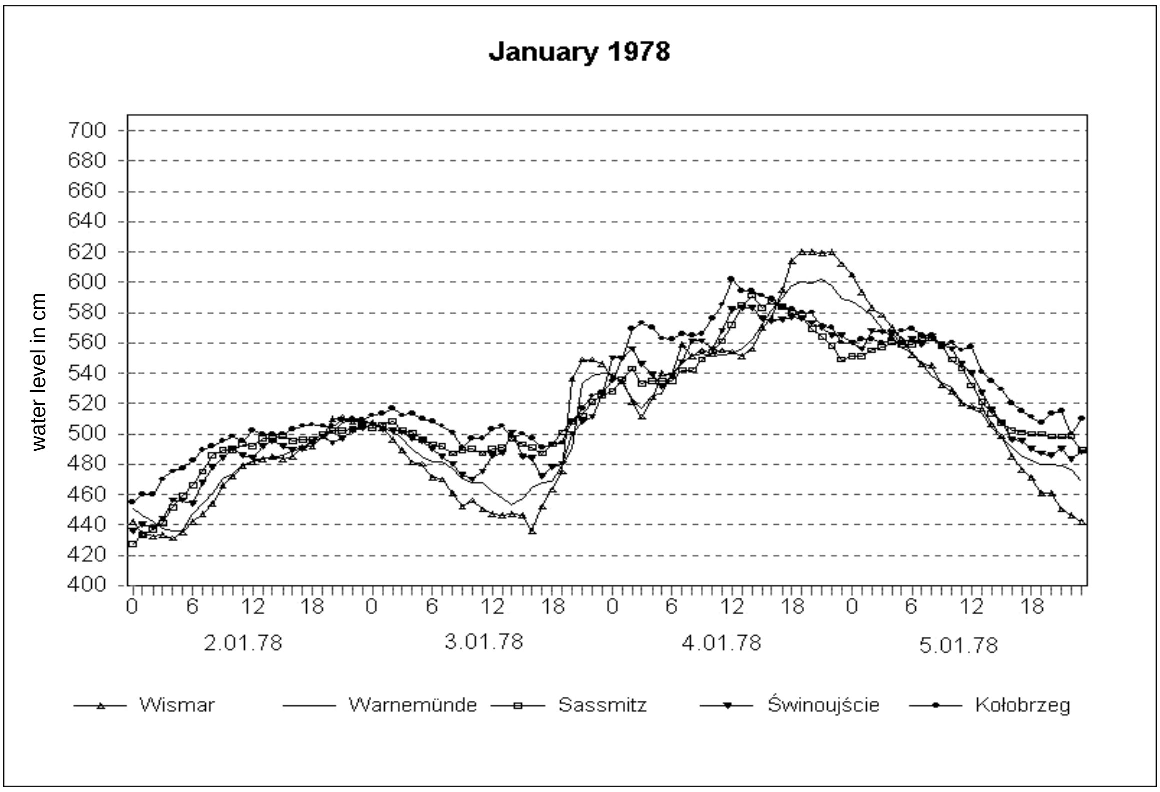

Fig. 6.3.2. Sea level changes during the storm surge of January 1978

6.4 <u>January 1983</u>

Meteorological situation

At the end of 1982 and beginning of 1983, stormy winds blew mainly from westerly directions, causing relatively high mean sea levels of the Baltic Sea.
On 17 January 1983, at about 18 UTC, a low pressure centre of 978 hPa formed over the Shetland Islands, which deepened rapidly and travelled east-southeast towards southern Norway and Sweden. Within 24 hours, this low with a pressure of 962 hPa in its centre had reached the northeastern Baltic Sea, where it slowed down while the air pressure grew steadily over the British Isles and the North Sea. At 00 UTC on 19 January, the depression moved across Latvia, where it began to fill rapidly, while a high pressure system spread and strengthened over Scandinavia and the Baltic Sea.
As a consequence of this atmospheric pattern, W to SW winds blew across the Baltic Sea, reaching gale force in the western parts of the basin on 17 January. On 18 January, a severe SW to W storm of 8-10 Bft raged across the Baltic Sea, which veered and reached 9-10 Bft, with 12 Bft in gusts (Fig. 6.4.1). During 19 January, as the low filled and moved east, the

storm gradually decreased to 10-8 Bft. On 20 and 21 January, NW to W winds of 7-8 Bft, with a decreasing tendency, were observed .

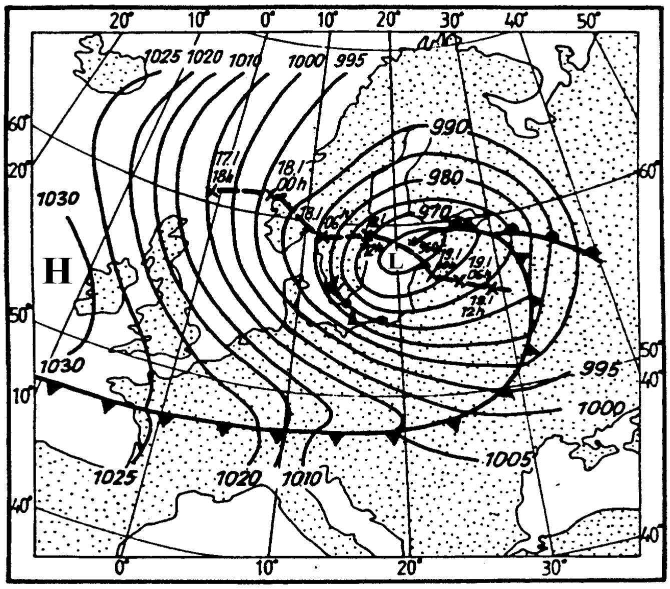

Fig. 6.4.1. Route of the low-pressure centre between 17 January, 18 UTC, and 19 January, 12 UTC; pressure pattern and wind field on 18 January 1983, 18 UTC

A more detailed study of the wind field along the southern coasts allows an analysis of the relationship between the impact of the wind and resultant sea level variations on the shores. On 18 January, the initially SW to W-SW alongshore winds of 7-8 Bft grew in force, reaching 10 Bft in gusts, and backed to offshore directions which were S-SW at times, especially in the westernmost parts of the basin. From about 9 UTC, however, winds on the southern Baltic coasts veered sharply, developing into a NW storm of 10-11Bft in the Bornholm area as early as noon. However, winds then began to veer W – NW (8-9 Bft) on the southern coasts, first in their central parts and later in the west. At about 18 UTC on 18 January, and about 00-03 UTC on 19 January, winds veered NW – N at 7-9 Bft, decreasing very slowly.

Hydrological response of the sea level

On the day preceding the storm, sea levels in the western part of the coast were insignificantly higher than the normal values (e.g. 500-510 cm in Wismar), and were moderately high in the central coastal area (e.g. 550 cm in Sassnitz and Świnoujście). The severe storm on 18 and 19 January, and especially the wind field pattern along the coast, initially (18 January) caused a further differentiation of water levels in the two coastal areas. Then, on 19 January, water levels on the entire coast rose rapidly and exceeded the alarm levels.
In the western part of the coast, the stormy offshore winds caused sea levels to fall by about 10 cm/h. Levels remained very low for about 8 hours, e.g. 410-415 cm at Wismar. On 19 January at midnight, when the wind veered suddenly WNW to NW, sea levels began to rise rapidly at a rate of 28-29 cm/h and reached their maximum on 19 January between 13 and 14 UTC. The maximum values in Wismar and in Warnemünde were 634 cm and 617 cm, respectively. The difference between the extreme values, which developed in the course of 18 hours, exceeded 220 cm in Wismar, and about 190 cm in Warnemünde.
Farther east, at about 9 UTC on 18 January, the immediate reaction of water levels to the wind impact is clearly seen in Kołobrzeg and, slightly less pronounced, in Świnoujście. Wind directions veer slightly and begin to oscillate between WSW and W, i.e. they sometimes blow

in an onshore direction. This is reflected in rapidly changing water levels (e.g. on 18 January between 7 and 8 UTC, the sea level at Kołobrzeg changes at a rate of 25 cm/h). As the gale-force winds back slightly offshore to a W-SW direction in the early afternoon of 18 January, sea levels fall, with lower levels recorded in Sassnitz and Świnoujście than in Kołobrzeg.
The impact of the NW storm progressing south of Bornholm is first felt in Kołobrzeg and Sassnitz, where the water level begins to rise at 15 UTC, and then in Świnoujście, at 16 UTC on 18 January. The culmination in this part of the coast is reached on 19 January at 9 UTC at Świnoujście (623 cm) and Sassnitz (624 cm) and only one hour later in Kołobrzeg, where the maximum is 640 cm.
In the western part of the coast, levels remained above the alarm water level (580 cm) for 17 hours in Wismar, 16 hours in Warnemünde, and 35 hours in Sassnitz. In the central part of the coast, they were above the alarm level (580 cm) for as long as 31 hours in Świnoujście, and 24 hours in Kołobrzeg (above 610 cm).
Relative to the reference level indicator (577 cm on 17 January), this surge lasted from 18 hours in Warnemünde to 38 hours in Kołobrzeg.

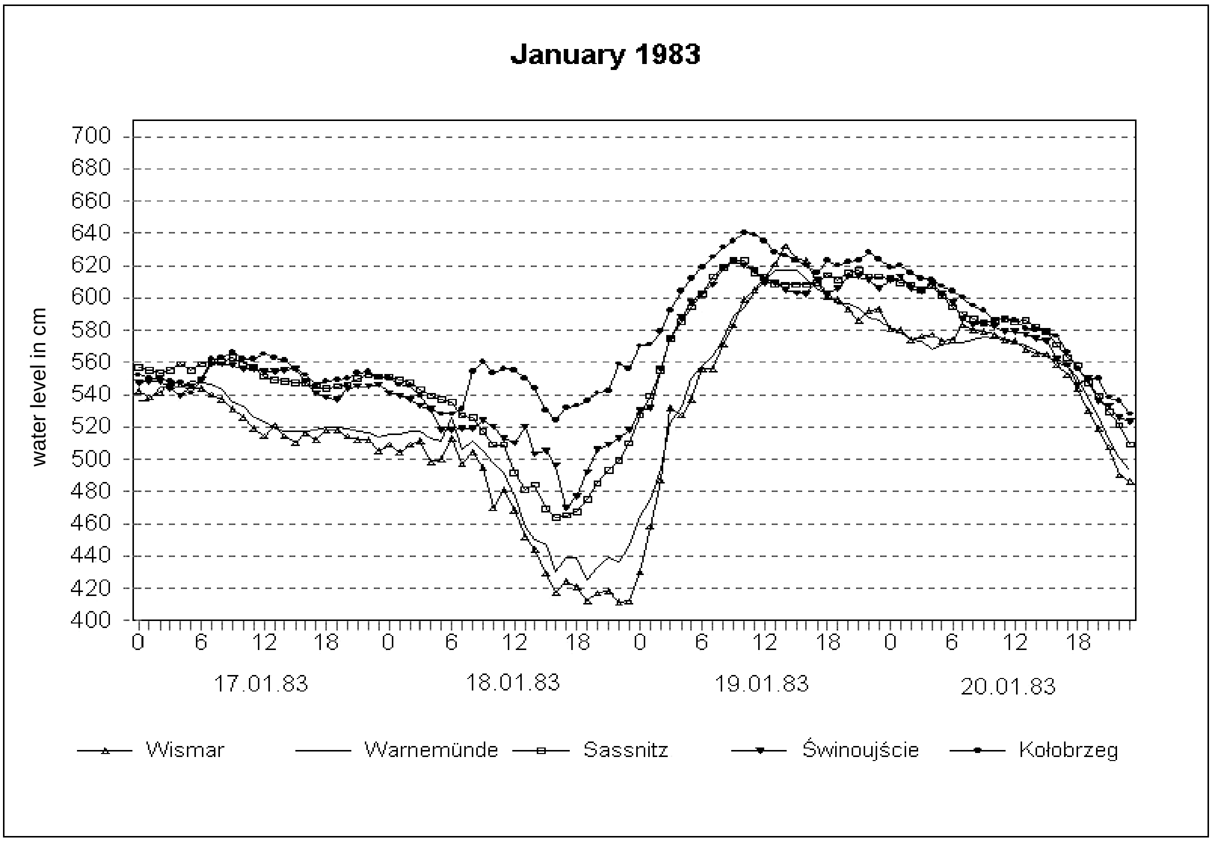

Fig. 6.4.2. Sea level changes during the storm surge of January 1983

6.5 February 1983

Meteorological situation

In a stable situation of zonal circulation over Europe (Fig. 6.5.1.), one of the low-pressure centres in a long series of eastward moving disturbances reached its lowest value of 954 hPa on 1 February, 03 UTC, over Scotland and, filling slowly, travelled rapidly east-southeast. In front of the approaching frontal system connected with the depression, the hitherto moderate winds over the western and southern Baltic Sea backed SE, increasing gradually. Between 9 and 15 UTC, the fronts crossed the western and southern Baltic Sea, and the low-pressure centre continued moving slowly southeastward across the entrance to the Skagerrak and northern Denmark toward the southern Baltic Sea, while over Western and Central Europe the air pressure increased considerably. This led to a dangerously steep pressure gradient resulting in a vehement SW–W storm of 8-9 Bft, which soon increased to 9-11 Bft in the southern North Sea. When the storm reached the western Baltic Sea around noon, the severity of the winds had decreased somewhat, at 7-8 Bft, and continued to decrease slightly as the storm travelled eastward. Late on 1 February, when the low pressure centre was over the southern Baltic Sea, one of the secondary fronts crossing the Danish Sounds caused the W-SW storm to veer sharply northwest over the western and southern Baltic Sea. As the centre of the low reached the Gulf of Riga on 2 February (Fig. 6.5.2.), at about noon, the storm continued to veer and became gusty, reaching 7-8 Bft with gusts of 9 Bft. At about 15-18 UTC, the pressure gradient started to weaken, but the onshore NW-SW winds continued for another two days, until around noon on 4 February.

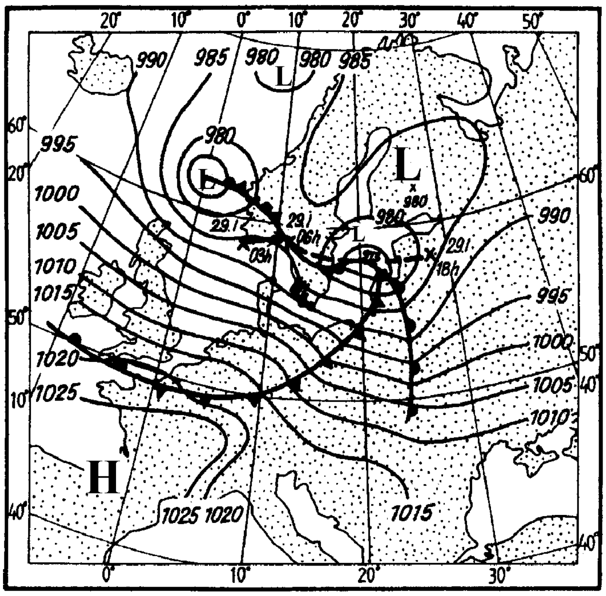

Fig. 6.5.1. An example of wind-driven forcing of surface water due to long-lasting zonal atmospheric flow, causing elevated water levels in the southern Baltic Sea. The pressure pattern on 29 January 1983: a successive low-pressure trough, which – within the intensive zonal air flow – moved across the North and Baltic Seas in the days preceding the storm surge on 2-4 February 1983.

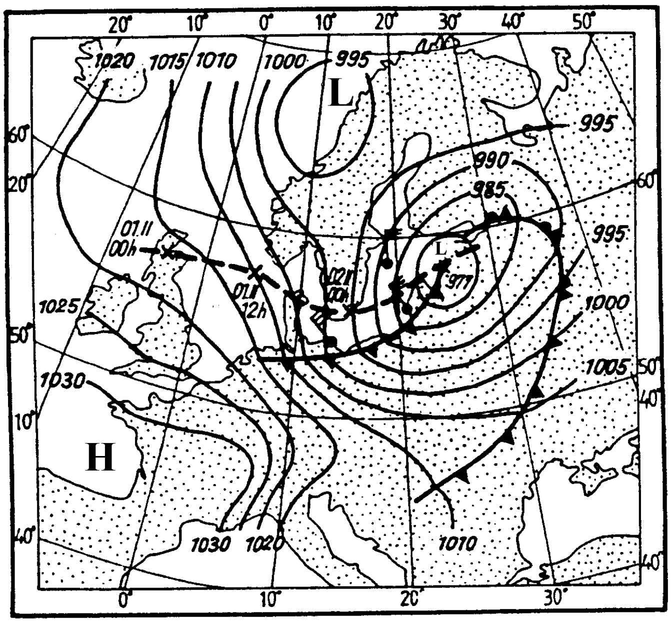

Fig. 6.5.2. Route of the depression from 1 February, 00 UTC to 2 February 1983, 12 UTC; pressure pattern and wind field on 2 February 1983, 12 UTC

Hydrological response of the sea level

Due to intensive westerly air flow over the North and Baltic Seas in the last days of January, 1983 (Fig. 6.5.1.), the prevailing westerly winds, which often reached gale force, caused relatively high water levels on the southern coast of the Baltic Sea, e.g. in the late morning hours of 1 February, when the mean sea level was exceeded by 30-70 cm.

About noon on 1 February, under the impact of the SW-W storm over the western Baltic Sea, which reached hurricane force at times, water levels in the area began to fall rapidly. In Wismar, for example, the water level dropped 136 cm in 10 hours. The minimum level, recorded at 21 UTC, was as low as 419 cm. The minimum in Warnemünde, one hour later, was 455 cm. Other water gauges recorded much flatter minima because farther east the southwesterly storm did not develop fully, being overtaken by the northwesterly air flow following the southbound front line.

When the NW storm struck the waters of the western Baltic in the late hours of 1 February, sea levels began to rise rapidly, but with an irregular pattern. For example, initial oscillations of the sea level at Wismar were followed by a rapid rise of sea level by 131 cm within 6 hours. The largest hourly increment was 47 cm/h, recorded between 09 and 10 UTC, while the total increase during this surge was 1.4-1.6 m. The maximum values were reached between 15 and 16 UTC: 613 cm in Wismar, 608 cm in Warnemünde, and 619 cm in Sassnitz. Two hours later, Świnoujście recorded 599 cm, and Kołobrzeg 627 cm. The culmination phase was shorter: about 4-5 hours.

The high water levels (exceeding 560 cm) of this surge lasted for about 16-22 hours and were followed by another gradual decrease to the warning level values. As successive troughs of low pressure, accompanied by rather intensive westerly to northwesterly air flow, moved across the Baltic Sea, sea levels in this area remained high until 5 February. Relative to the reference level indicator (568 cm on 2 February), this surge lasted from 14 hours in Wismar to 33 hours in Kołobrzeg.

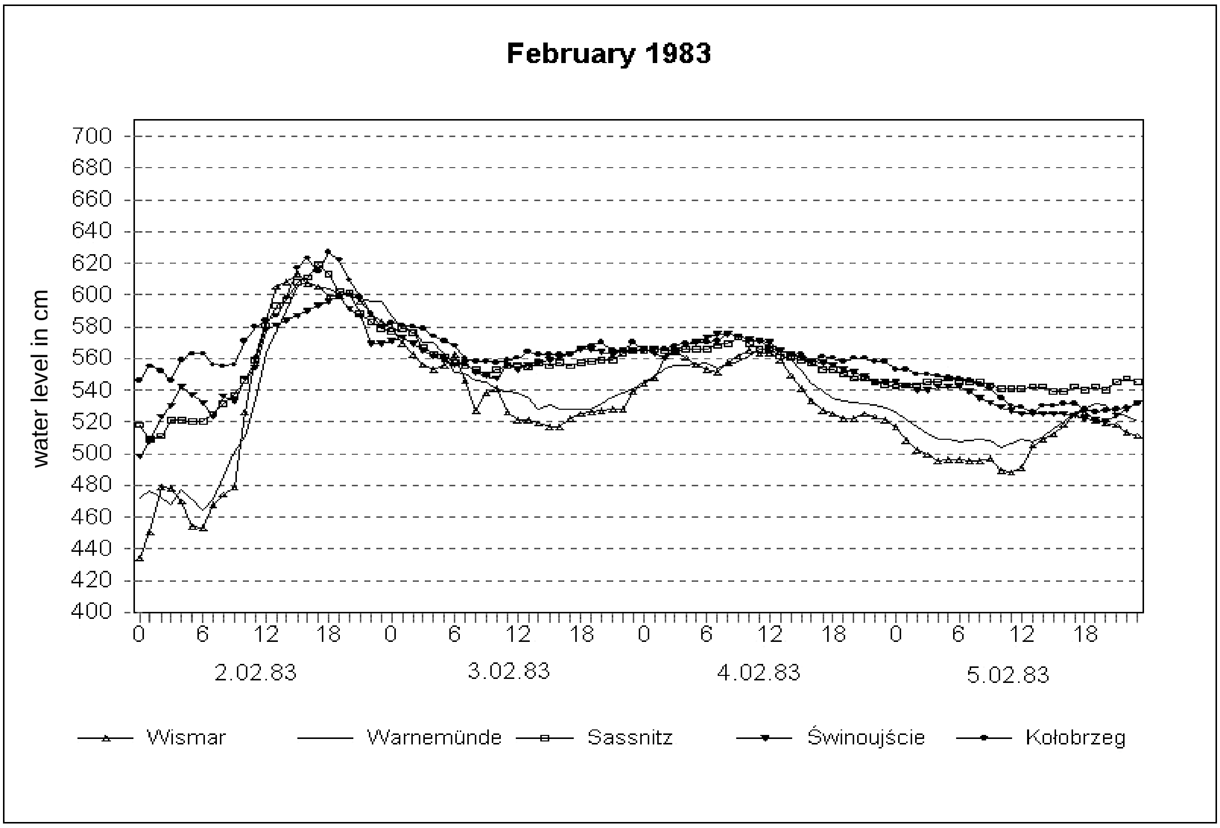

Fig. 6.5.3. Sea level changes during the storm surge of February 1983

6.6 November 1983

Meteorological situation

On 26 November 1983, the Baltic Sea was under the influence of a low-pressure trough, with a moderate to strong southwesterly air flow. Later on this day, at about 18 UTC, a new and very active disturbance (971 hPa) appeared to the west of Ireland (at about 52ºN, 20ºW) and, deepening, travelled rapidly east. Within a few hours it covered the distance to the British Isles, crossed them and reached the southern North Sea at about midnight. Here it nearly stopped, probably blocked by a high pressure ridge over Scandinavia, before continuing slowly east-northeast. The depression continued to deepen, with 954 hPa recorded at noon on 27 November, as it reached the continent near the estuary of the river Weser. It now travelled across land along the southern coasts of the North and Baltic Seas (Fig. 6.6.1.), reaching south-western Bielorussia on 29 November, with 984 hPa measured in its centre. Afterwards its influence on the wind field over the Baltic Sea ceased.
In consequence of this pressure pattern, NE – E winds set in over the northern Baltic Sea on 27 November. In the central areas, the winds backed SE and later E, while southeasterly directions prevailed over the western Baltic until the evening, when the entire area was affected by the increasing northeasterly gale. Early on 28 November, an E – NE storm of 8 Bft developed over the whole Baltic Sea (Fig. 6.6.1.), backing N and reaching 9 Bft. In the afternoon of this day, the winds decreased gradually to 6-5 Bft in the western Baltic areas, and 7-6 Bft in the northern Baltic Sea.

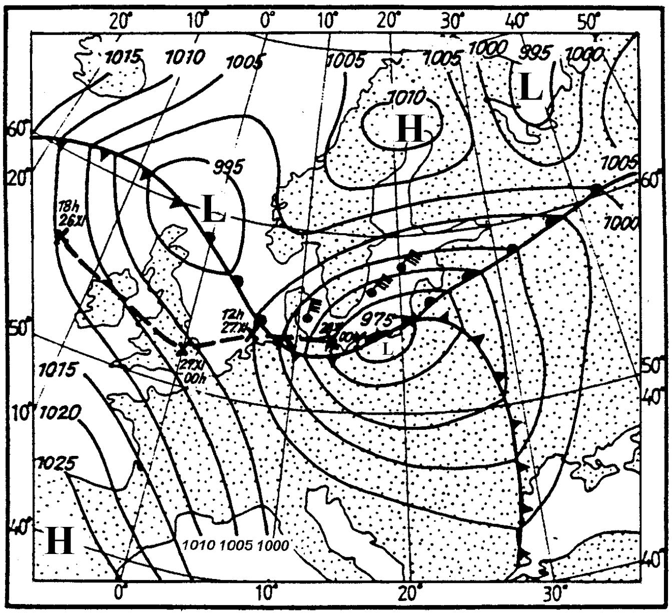

Fig. 6.6.1. Route of the stormy low-pressure centre between 26 November and 28 November 06 UTC; pressure pattern and wind field over the Southern Baltic Sea on 28 November 1983 at 06 UTC

Hydrological response of the sea level

On 26 and 27 November, when the gradual rise of sea levels began, moderate offshore to alongshore winds (SW, backing SE - E) prevailed both in the western and central parts of the southern Baltic coast. The rise of sea levels resulted from the forcing exerted by the long-fetch easterly wind, which drove the surface water towards the western basins. Levels there rose to about 570 cm (Wismar, Warnemünde, Sassnitz) in the morning of 27 November, and remained at this level for nearly 12 hours (e.g. from 8 to 19 UTC in Wismar). Then, at about 20 UTC on 27 November, as the centre of the storm continued eastward, the direct impact of the stormy northerly wind on the western part of the coast caused sea levels to rise 40 cm within two hours. Levels then oscillated slightly between 620 and 645 cm during the culmination stage, which lasted for 14 hours (Wismar). The maximum of 646 cm was recorded in Wismar on 28 November, at 11 UTC. Warnemünde recorded 634 cm, and Sassnitz 619 cm. In the central area of the coast, the rapid increase began later, and the culmination phase, though of equal duration, occurred later, e.g. in Kołobrzeg about 8 hours later than in Wismar. The maximum levels were lower: 613 cm in Świnoujście at 13 UTC, and 612 cm in Kołobrzeg at 11 UTC on 28 November.

During this surge, the mean sea level was exceeded by 1.1 to 1.5 m. The warning stages lasted 31 to 50 hours along these parts of the coast, and the alarm level more than 20 hours. Relative to the reference level indicator (552 cm on 26 November), this surge lasted from 39 hours in Świnoujście to 54 hours in Sassnitz.

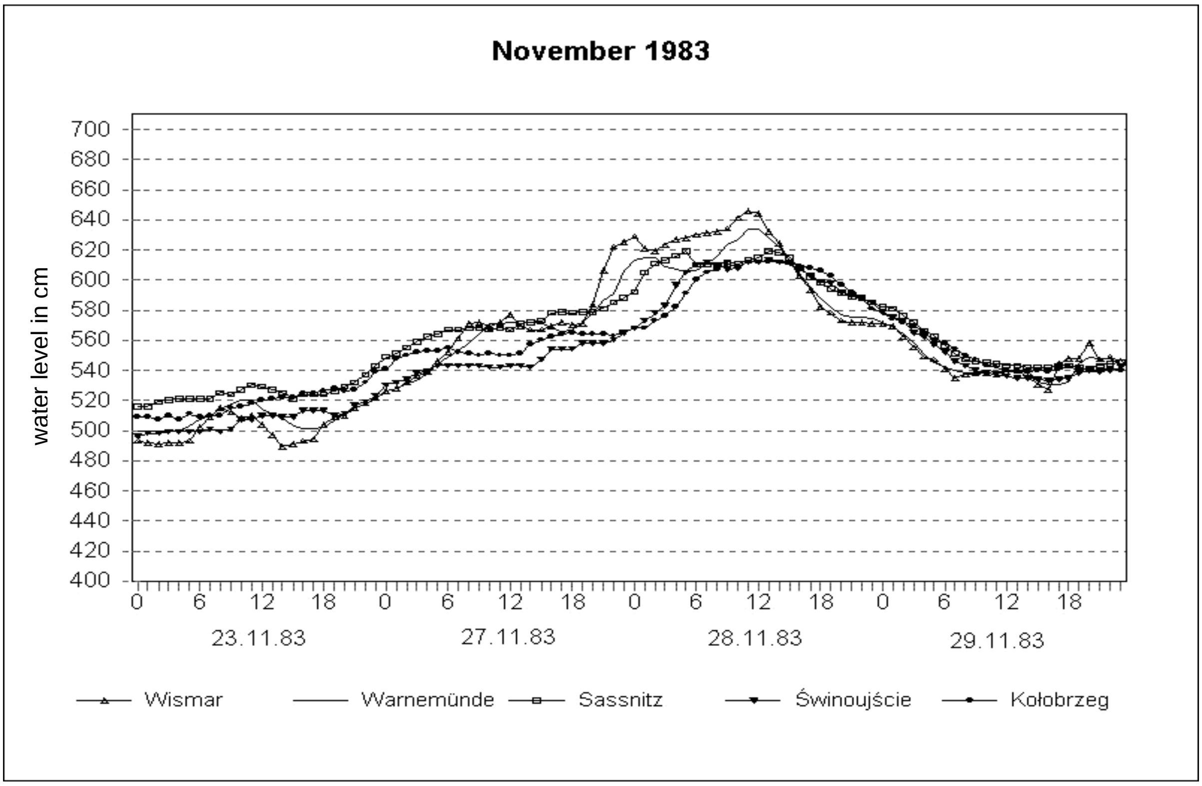

Fig. 6.6.2. Sea level changes during the storm surge of November 1983

6.7 October 1986

Meteorological situation

On 19 October, a light to moderate SW – SE air flow prevailed in the Baltic Sea region until, in the afternoon of 20 October, an active low-pressure centre approached from Ireland, which crossed the southern North Sea and, still deepening, arrived over the southwestern Baltic Sea at about 21 UTC. The pressure in the centre was 973 hPa.

Before the approaching storm centre, which tracked east following a route close to the coastline, the winds backed SE – E, and NE farther offshore, growing in force to 7 Bft. In a narrow zone of a very steep pressure gradient in the rear of the low, behind the occluded front, a northerly to northwesterly storm reaching 8-9 Bft in some places struck the western coast at 21 UTC on 20 October. The onshore storm spread gradually eastwards, while the pressure gradient over the western Baltic Sea weakened (Fig. 6.7.1.). At 12 UTC, the low pressure centre (982 hPa) crossed the Lithuanian coastline and moved east, so that between 12 and 15 UTC only the coasts of the Gulf of Gdańsk still felt the impact of the northwesterly storm.

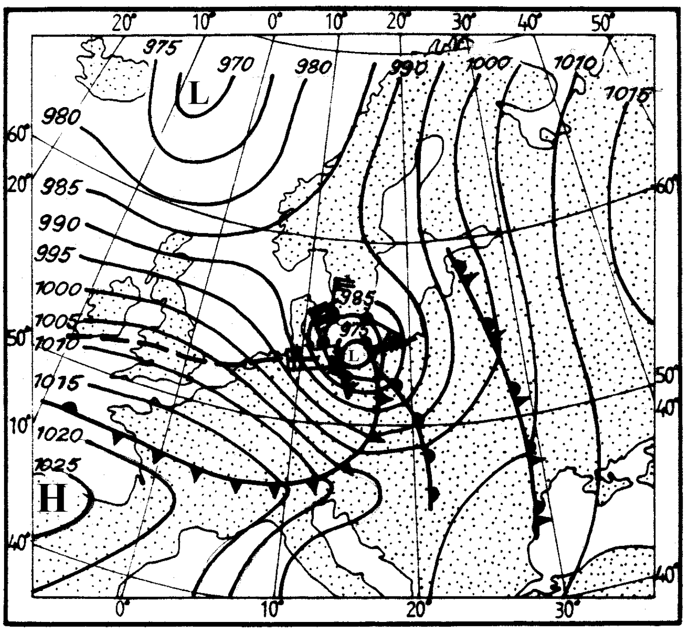

Fig. 6.7.1. Route of the stormy low-pressure centre between 19 October and 21 October 12 UTC; pressure pattern and wind field over the southern Baltic Sea on 21 October 1986 at 06 UTC

Hydrological response of the sea level

On 20 October, water levels in the western part of the southern Baltic coast rose gradually from low values at the beginning of the day to mean levels later in the day, while in the central part they oscillated slightly around the mean levels.
In the westernmost part of the coast, at about noon, offshore winds in front of the approaching stormy depression caused sea levels to fall slightly, after which they rose again somewhat when the centre of the low reached the water gauges during the afternoon. Levels then rose quickly when the wind shear line (the occluded front) passed southward and the onshore N – NW storm struck the coast. At 21 UTC, the level at Wismar rose more than 1 m in one hour, probably due to the impact of a so-called long wave (formed along the wind shear line and moving together with the progressing atmospheric front). The peak value of 619 cm was recorded at 00 UTC. Levels then dropped a little and, in the field of the slightly weakening onshore storm, fell to normal values within a few hours.
Similar changes of sea levels were recorded in the central part of the coast, where a time lag of 6-9 hours was observed. At first, between 12 and 19 UTC on 20 October, sea levels fell slightly (by about 40 cm) in Świnoujście and Kołobrzeg due to the impact of the offshore southeasterly storm in front of the approaching low. The increase began about midnight, the rate of growth being at first moderate and considerably higher lateron. The maximum recorded in Sassnitz between 02 and 05 UTC on 21 October was flat. In Świnoujście, the maximum was sharper and reached 590 cm, with a culmination between 6 and 7 UTC. In this part of the coast the maximum hourly increments were considerably smaller than in the west: 22 cm/h in Świnoujście and 54 cm/h in Kołobrzeg. Relative to the reference level indicator (509 cm on 19 October), the duration of this surge ranged from 15 hours in Wismar to 24 hours in Sassnitz.

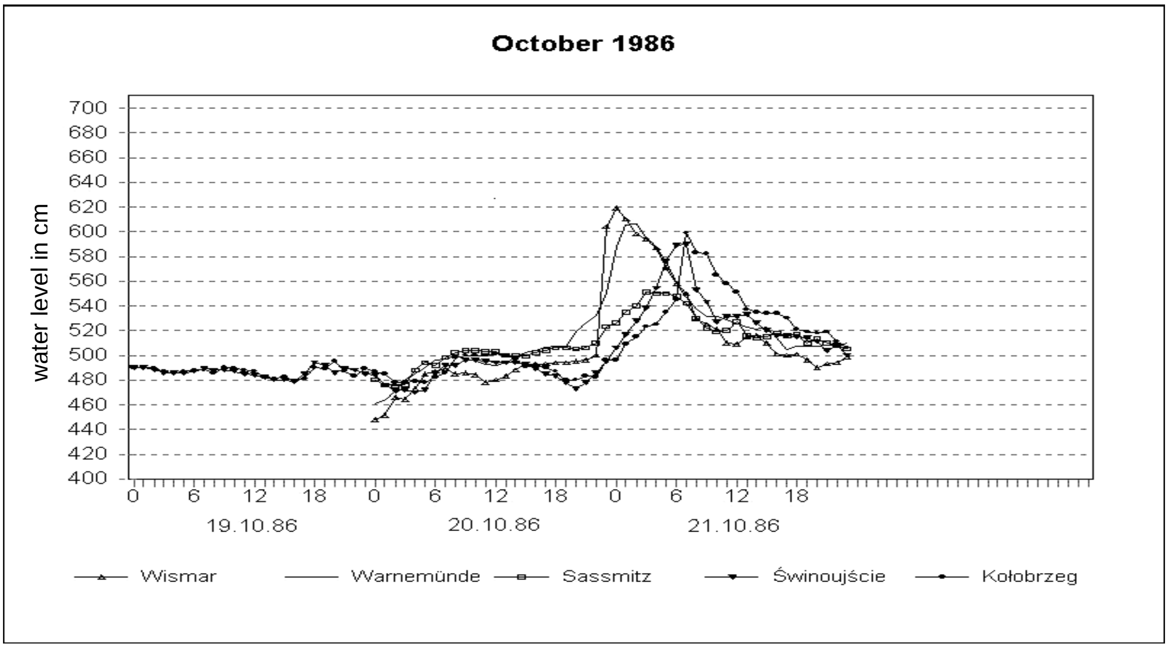

Fig. 6.7.2. Sea level changes during the storm surge of October 1986

6.8 January 1987

Meteorological situation

In a low-pressure trough adjoing the western edges of a high-pressure ridge (1030 hPa) over Scandinavia, an active low-pressure centre formed over the Skagerrak in the early hours of 8 January. Moving slowly southeastwards, the low continued to deepen. The frontal system connected with this low reached the coasts of the southern Baltic Sea in the afternoon and advanced south-southeast across Poland on 9 January (Fig. 6.8.1.).

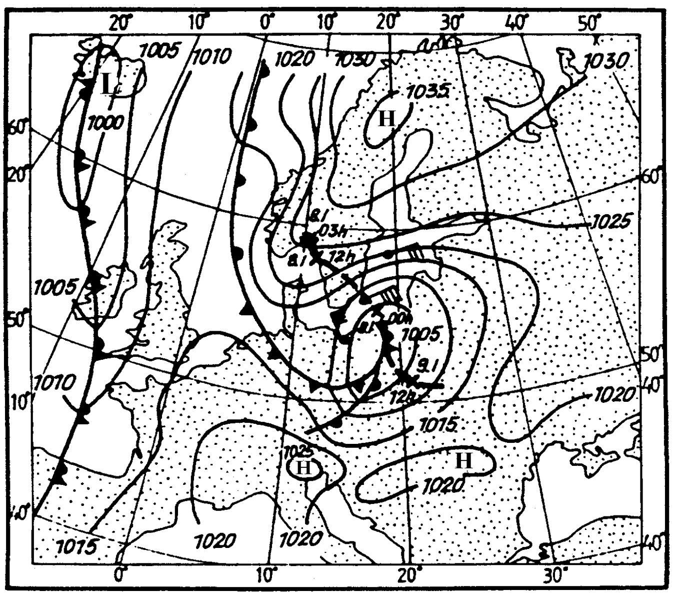

Fig. 6.8.1. Route of the low-pressure centre between 03 UTC on 8 January and 18 UTC on 9 January; pressure pattern at 03 UTC on 9 January 1987 and the accompanying wind field over the southern areas of the Baltic Sea.

On 8 January, light to moderate W – SW and SE winds prevailed over the southern basins of the Baltic Sea. As the low approached, the winds veered SW and reached moderate to high wind speeds in the western Baltic Sea. A NW – N storm of 6-8 Bft developed in the rear of the low and struck the coasts of the Wismar Bight around 15 UTC on 8 January and then, around midnight, with even higher severity, the coast of the Pomeranian Bight and parts of the central coast. In the early hours of 10 January, the storm, which had veered NE, gradually abated as the low retreated southwards.
Over the southern Baltic, however, the northeasterly gale continued with varying intensity. Very strong gusts were recorded, which were due to extremely cold continental air masses over the sea (coastal stations reported that on 10 January, at 6 UTC, Kaliningrad recorded -22 ºC, Klaipeda -25 ºC, Liepaja -26 ºC, Riga –31 ºC and Helsinki -35 ºC), the southern parts of which were not completely covered by ice.
On 11 January, the atmospheric pressure in the anticyclone over Scandinavia rose to 1052 hPa. The steepest gradient, along with a steady NE storm of 8-10 Bft, occurred on the southern and southeastern coasts of Sweden. The storm reached its maximum between 06 and 21 UTC on 12 January, when a wide and flat zone of lower pressure began to form over Central Europe, tending to drift northwards. The zone with the steep gradient and strongest wind moved towards the Scandinavian coast and the westernmost part of the western Baltic Sea, while the southern and southeastern Baltic Sea remained in a field of somewhat weaker winds blowing mostly alongshore (Fig. 6.8.2.). It was not until about 00 UTC on 13 January that winds on the southern coast began to decrease, although farther offshore and over the Baltic Proper the easterly storm continued for several days.

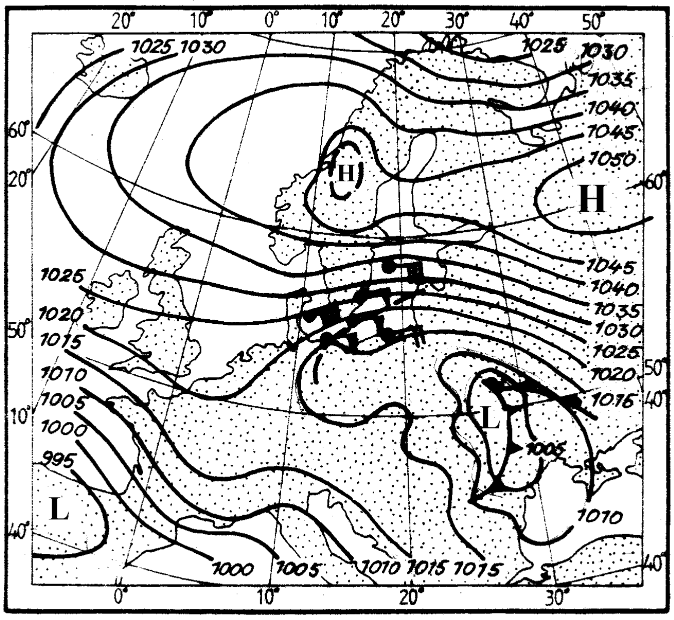

Fig. 6.8.2. Pressure pattern and accompanying wind field at 18 UTC on 12 January 1987 over the southern areas of the Baltic Sea

Hydrological response of the sea level

During the surge of 8 - 9 January, 1987, water levels rose first in Wismar and Warnemünde (between 12 and 15 UTC on 8 January), when winds in the area veered NW, nearing gale force. Between 18 and 21 UTC, in response to the onset of a northwesterly to northerly storm of 7-8 Bft in the rear of the cold front, sea levels in the central part of the coast rose rapidly. Culmination was first reached in Sassnitz (605 cm at about 03 UTC on 9 January), which also recorded the highest mean rate of growth, at an average 10 cm/h (111 cm in 11 hours). Culmination was next reached in Świnoujście, 612 cm at about 07 UTC with an average increase of about 9 cm/h, and Kołobrzeg with a two-peaked maximum of 607 and 609 cm between 07 and 10 UTC. In Wismar and Warnemünde, where the initially northerly gale of 6-7 Bft developed into a northeasterly storm of 7-8 Bft between 09 and 13 UTC on 9 January, the culmination developed last. The maximum levels of 611 cm in Wismar and 600 cm in Warnemünde were reached at about 13 UTC at both gauges (Fig. 6.8.3.).

The maximum rate of increase ranged from 24 cm/h in Kołobrzeg, recorded between 05 and 06 UTC, to 11 cm/h in Warnemünde, recorded at about 00 UTC on 9 January. The water stayed above warning levels for nearly 20 hours. Relative to the reference level indicator (which on 9 January was as high as 520 cm), the duration of this surge was 33 hours.

The second phase, on 12-13 January, was characterised by a slower rise of sea levels, which began in the afternoon of 11 January. In the central part of the coast, levels above the warning values were only recorded on the coasts of the Pomeranian Bight, where the maxima between 17 and 19 UTC on 12 January did not exceed 599 cm in Świnoujście (between 14 and 16 UTC), and 614 cm in Sassnitz. Sea levels in the area began to fall as soon as the zone of weaker SE veering winds had reached the area northwest of Bornholm and Rügen (Fig. 6.8.2.). The culmination in Warnemünde was recorded between 22 and 23 UTC on 12 January and was as high as 642 cm. The sea level at Wismar decreased last, where the maximum of 673 cm was recorded between 00 and 01 UTC on 13 January.

Based on the reference level indicator (519 cm on 11 January), the second phase of the surge lasted from 77 hours in Kołobrzeg to 90 hours in Warnemünde.

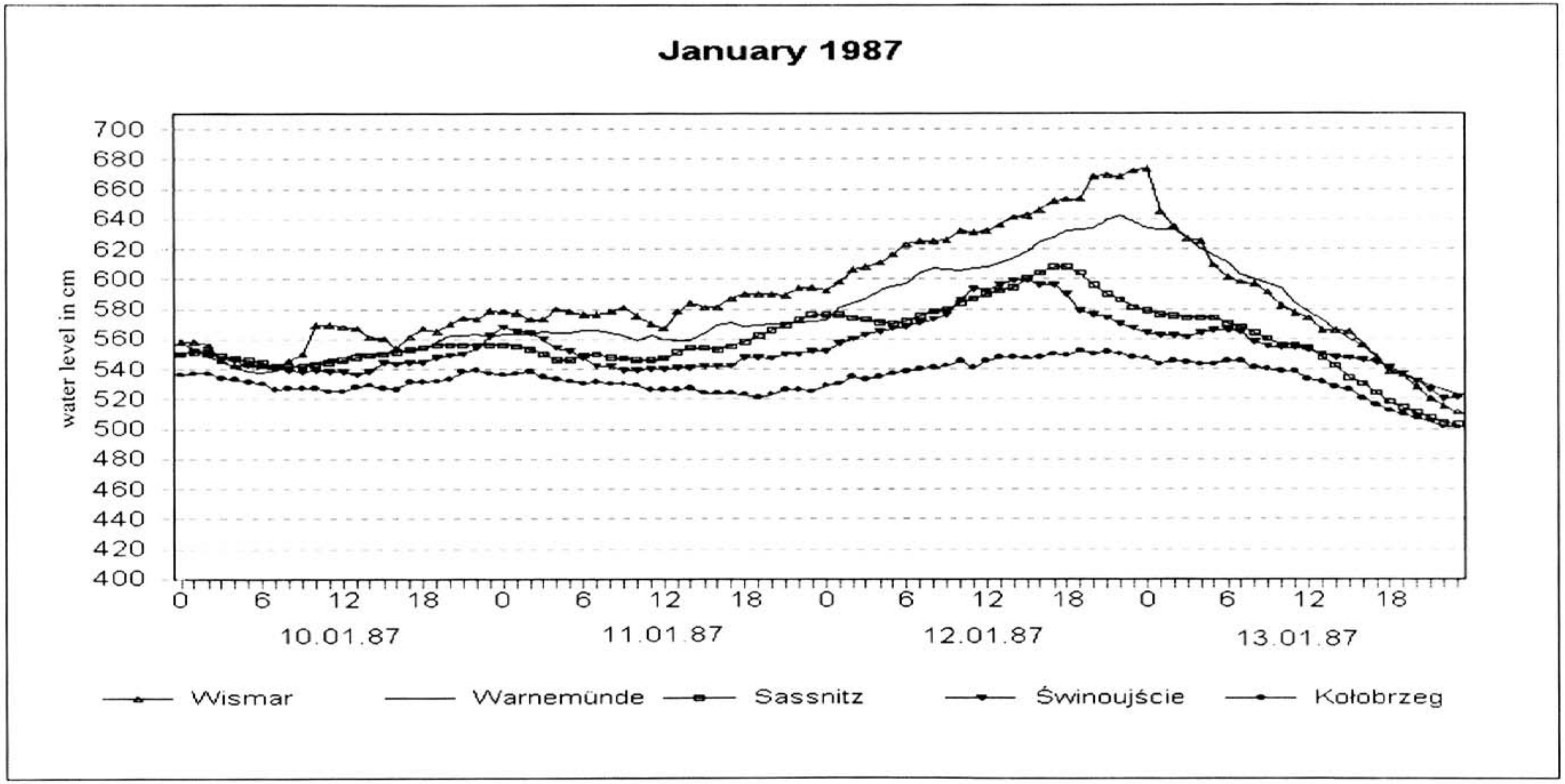

Fig. 6.8.3. Sea level changes during the storm surges of January 1987

6.9 November 1988

Meteorological situation

At the end of November, 1988, numerous cyclones moved from the North Atlantic across Scandinavia and the Baltic Sea. On 28 November at about 06 UTC, a large cyclone off Scotland with an atmospheric pressure of 992 hPa in its centre deepened quickly and moved east-southeastwards. By 29 November, 06 UTC, the low had reached southern Scandinavia and, at 18 UTC on the same day, it reached Lithuania with a pressure of 969 hPa in the centre of the depression (Fig. 6.9.1.). The low-pressure system was accompanied by an occluded front with sharply veering winds. On 29 November, after the occluded front had crossed first the western and southern Baltic Sea and then the southeastern basins, the initially S-W gale-force winds of 7-9 Bft rapidly veered NW–N . However, the zone of the steepest gradient moved gradually westwards, so that the strongest northerly storm of 8-10 Bft first struck the eastern, central and, in the afternoon, western coasts of the Baltic Sea. Late on 29 November, the wind began to decrease in the central coastal areas and, early on 30 November, in the western parts. In the morning of 30 November, the wind decreased from 8 to 5 Bft.

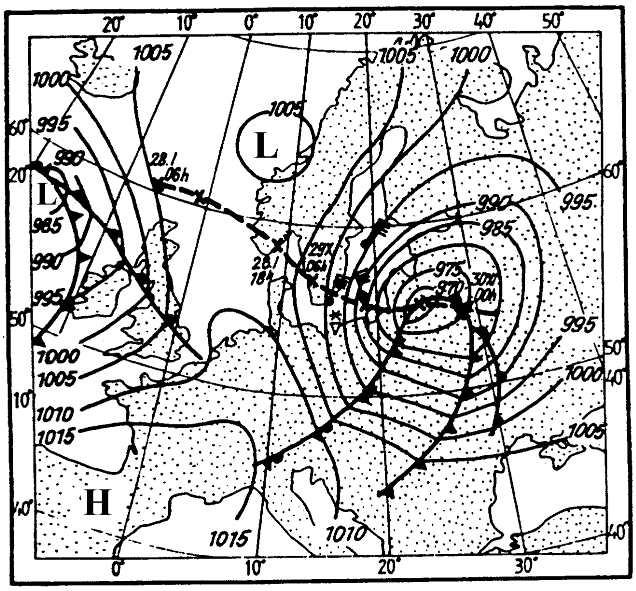

Fig. 6.9.1. Route of the low-pressure centre from 28 November, 18 UTC, to 30 November, 00 UTC; pressure pattern and wind field over the Baltic Sea on 29 November 1988, 18 UTC

Hydrological response of the sea level

The water level began to rise around 09 UTC on 29 November due to a slightly onshore, stormy wind field (up to 10 Bft) before the occluded front that accompanied the depression, which had its centre southwest of Gotland. Around noon, a squall line crossed the coast. Disturbances of the wind field along this squall line, especially directional disturbances, caused oscillations of coastal water levels: between 11 and 13 UTC, Wismar first recorded a decrease of sea level, which at that time was hardly detectable at Sassnitz. Between 12 and 14 UTC, it was clearly recorded in Świnoujście and Kołobrzeg. Later, as the northerly and northwesterly storm established itself over the whole Baltic Sea, the rise of sea levels continued until culmination was reached, first in the central part of the coast and later in the western part.
Culmination on 29 November was first recorded in Kołobrzeg, at 647 cm, Świnoujście at 621 cm, and Sassnitz at 620 cm. Characteristic features of this wind set-up were two peaks of

634 cm and 642 cm at 12 and 22 UTC, respectively, which were recorded at Kołobrzeg in the central part of the coast. The maxima of 647 cm in Wismar and 628 cm in Warnemünde were recorded at the same time: on 30 November at 03 UTC. After the maxima had been reached, water levels fell slowly as the wind abated on 30 November.
During this storm surge, the maximum rate of sea level increase was as high as 25-32 cm/h in the central coastal area, and 16-23 cm/h in its western part.
The alarm levels on all water gauges were exceeded and remained at that level for 9-14 hours. Relative to the reference level indicator (522 cm at 09 UTC on 29 November), the surge lasted from 25 hours in Wismar to 40 hours in Kołobrzeg.

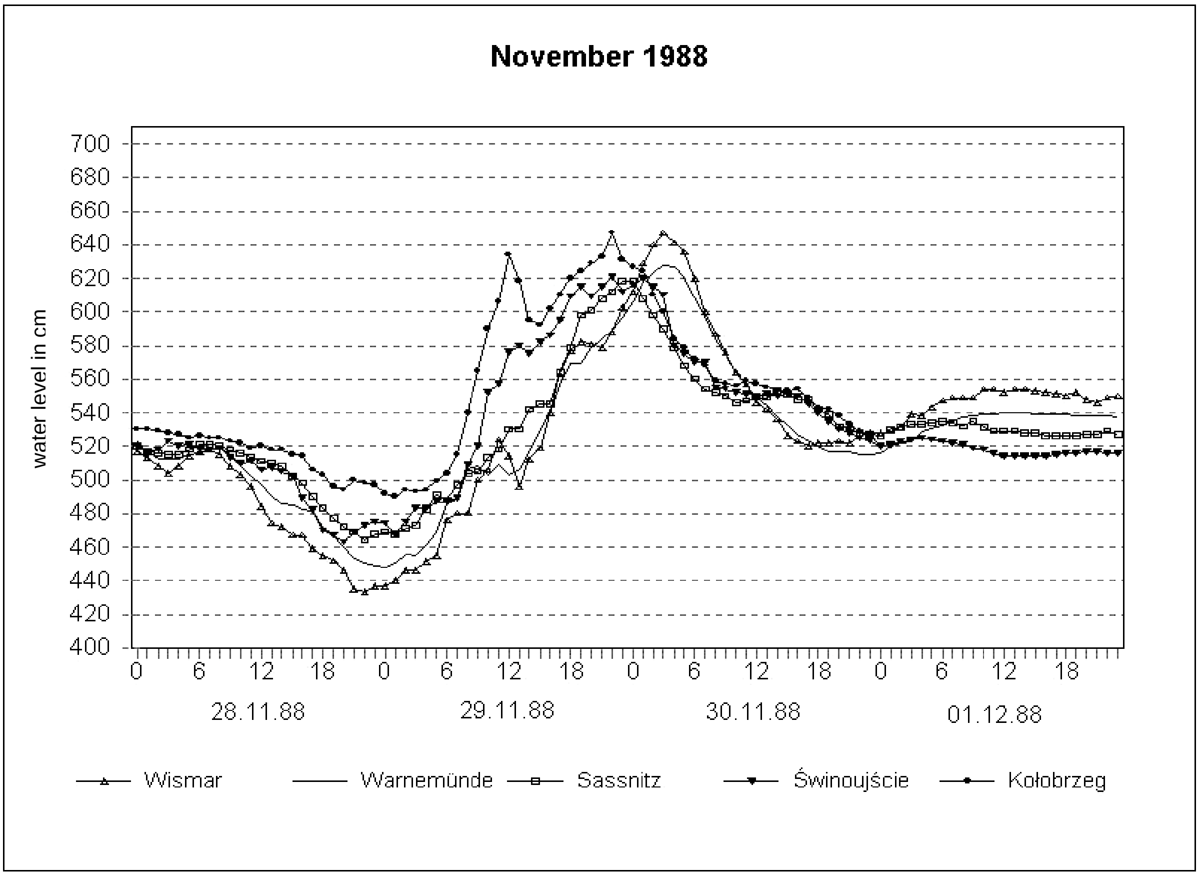

Fig. 6.9.2. Sea level changes during the storm surge of November 1988

6.10 December 1989

Meteorological situation

On 5 December 1989, the Baltic Sea was on the eastern side of an anticyclone over the British Isles, while to the east it bordered on a wide depression over Russia. A moderate to strong NW air flow developed over the Baltic Sea. In the night of 5 December, a large depression (975 hPa over the Norwegian Sea) began travelling across Scandinavia, passing over the Sea of Bothnia to the northern Baltic Sea, where it backed and, deepening intensively, moved across Estonia toward Russia. While the depression was on its way east, a very active trough with a system of atmospheric fronts, connected with the withdrawing low over the Baltic Sea, moved southwards. On 5 December and in the morning hours of the next day, this pressure pattern led to an intensive, stormy SW air flow over the whole area of the Baltic Sea.
Around noon on 6 December, a warm front reached the southern Baltic coasts, first its eastern and central sections, and several hours later also the western parts. Behind the front line, the wind veered W and later NW, increasing to 9 Bft. In the early and late morning hours

of 7 December, successive fronts crossed the coast. The northwesterly storm continued to veer and temporarily reached 12 Bft (Fig. 6.10.1.), after which it decreased slowly. As the low pressure centre moved eastwards, filling very slowly, and the anticyclone over Scandinavia persisted, the pressure gradient between the two centres remained steep enough to maintain strong winds over the Baltic Sea for many hours. However, between 12 UTC on 7 December and 6 UTC on 8 December, the atmospheric pressure in the region west of Denmark and over the western Baltic Sea decreased as a minor local cyclonic disturbance began forming in the region of Kattegat and southern Sweden. This led to initially decreasing winds, which then backed SW again and increased, blowing as a strong offshore wind over the western Baltic Sea for several hours.

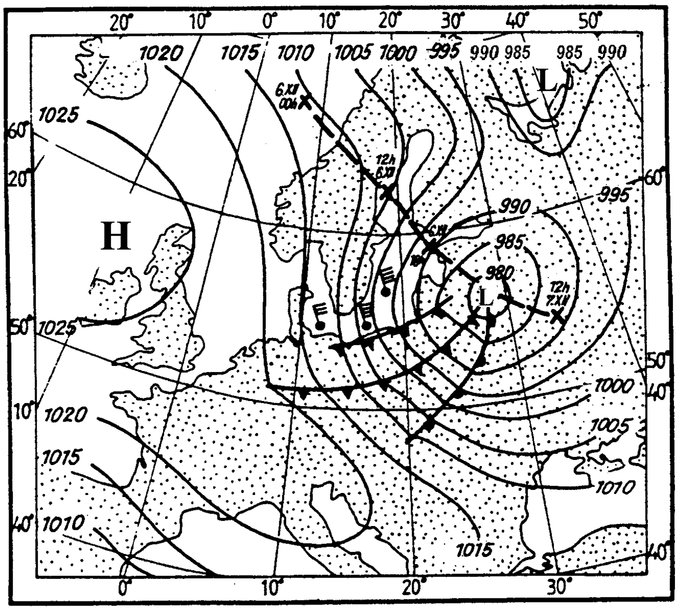

Fig. 6.10.1. Route of the stormy depression from 00 UTC on 6 December 1989 to 12 UTC on 7 December; pressure pattern and wind field at 06 UTC on 7 December 1989

Hydrological response of the sea level

The southwesterly offshore storm on 5 and 6 December caused water levels to decrease slowly to 450 - 470 cm. This effect was more pronounced in the western part of the coast. In the central part of the coast (Kołobrzeg), the water gauge did not indicate levels below 489 - 490 cm (between 07 and 11 UTC), while in Wismar the minimum level recorded only about 10 hours later, between 16 and 17 UTC on 6 December, was as low as 448 cm. These differences increased as the pre-frontal zone of strong southwesterly wind crossed particular sections of the coast. Culmination was reached on 7 December between 11 and 15 UTC, depending on the position of the tide gauge. Maximum values varied between 633 cm in Wismar and 605 cm in Świnoujście (Fig. 6.10.2.).

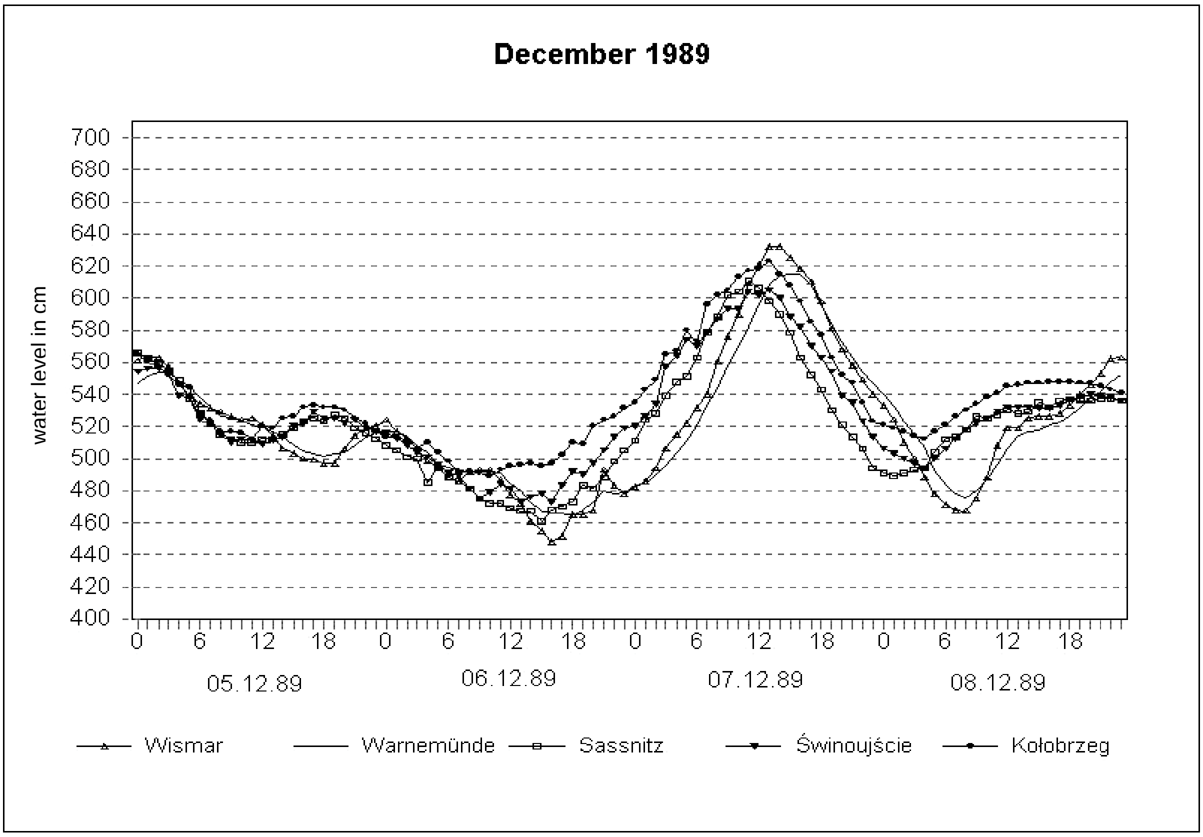

Fig. 6.10.2. Sea level changes during the storm surge of December 1989

As the surge was preceded by comparatively low water levels, it reached a considerable amplitude ranging from 1.8 m in the western part to 1.3 m in the central parts of the coast, with water levels in these areas rising by an average 12.6 and 6,3 cm/h, respectively. The alarm levels were exceeded at all gauges, and sea levels remained high for periods ranging from 7 hours in Sassnitz to 12 hours in Kołobrzeg. Referred to the reference level indicator of 513 cm on 6 December, this surge lasted from 21 hours in Wismar to 33 hours in Kołobrzeg.
The final phase of the surge decay was accelerated by additional forcing due to stormy offshore winds in the western coastal zone of the Baltic Sea in the late hours of 7 December and on the next morning. This caused sea levels to drop to rather low values (467 cm in Wismar and 475 cm in Warnemünde on 8 December at 08 UTC) only a short time after the maximum had been reached. As soon as the wind abated and the water was no longer forced away from the coasts, sea levels in the western section of the coast returned to rather high values (560 cm in the western part, 550 cm in the central part of the coast) in the afternoon and late hours of 8 December.

6.11 <u>January 1992</u>

Meteorological situation

On 16 January, Scandinavia and the Baltic Sea were influenced by a wide and deep depression (985 hPa) which moved slowly northwards from its position over Lake Ladoga. A secondary depression forming over the Norwegian Sea began to deepen and travelled southeastwards in the early hours of 16 January. It moved across central Scandinavia, the Åland Isles, Estonia and Latvia in one day, and its centre, with an atmospheric pressure as low as 982 hPa, reached the western parts of Bielorussia on 17 January, 06 UTC.

Meanwhile, a developing anticyclone over the British Isles was spreading eastwards across the North Sea, Scandinavia, and the Baltic Sea (Fig. 6.11.1.).
In the night of 16 January, the prevailing westerly winds of 6-7 Bft in the area of the Baltic Sea veered rapidly NW - N, increasing to 7-9 Bft first on the central coasts (around midnight on 16 January), and somewhat later (about 05 UTC on 17 January) also in the western parts of the coast. The storm lasted until 17 January around noon. As soon as the easward tracking depression over Bielorussia had filled and the Baltic Sea had come under the influence of the anticyclone, the wind backed again slowly, especially in the western parts of the coast, and decreased to 8-6 Bft, with a downward trend. The wind continued backing to offshore directions, blowing temporarily SW on 18 January, especially in the western parts of the coast.

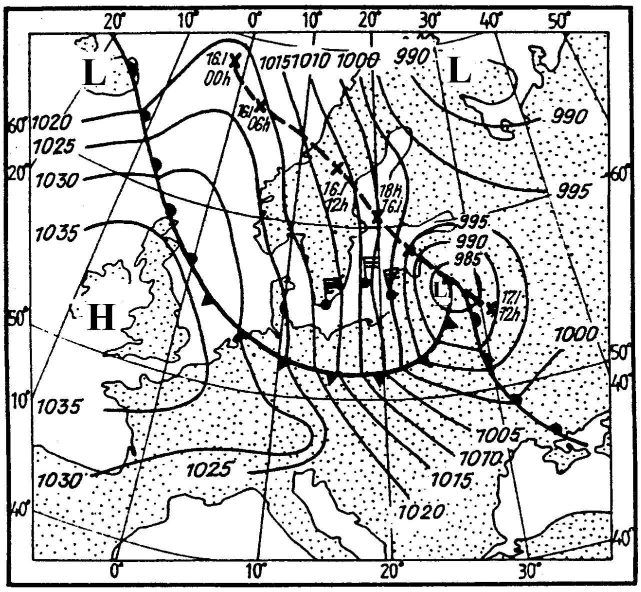

Fig. 6.11.1. Route of the stormy depression from 00 UTC on 16 January 1992 to 12 UTC on 17 January; pressure pattern and wind field at 06 UTC on 17 January 1992

Hydrological response of the sea level

The impact of the onshore wind in the night from 16 to 17 January resulted in a wind set-up which began in the central part of the coast (shortly before midnight on 16 January) and spread westwards, causing the sea level in Wismar to rise from about 05 UTC on 17 January. The highest level of 640 cm was recorded in Kołobrzeg on 17 January at 08 UTC, about the same time at which a peak of 616 cm was recorded in Świnoujście. At Sassnitz, the maximum of 636 cm was recorded two hours later, and at Warnemünde, slightly above 598 cm, between 11 and 12 UTC. The maximum level at Wismar was 613 cm at 12 UTC (Fig 6.11.2).
From about 22 UTC on 16 January, the water rose about 1 m within 12 hours (in Kołobrzeg only 9 hours). The maximum rate of increase, 31 cm/h, was observed in Kołobrzeg, and 30 cm/h was recorded in Wismar. The mean rate of increase varied from 9 to 12 cm/h in the central part of the coast and from 11 to 14 cm/h in the western part. High water levels (exceeding 580 cm) persisted for 8 hours in Warnemünde, and 14 hours in Kołobrzeg, after which a decay was observed which was more uniform in the central parts.
The about 30 cm higher levels in the central part of the coast during the culmination phase of the surge resulted not only from stronger winds with prevailing onshore directions but also from the somewhat higher (by about 30 cm) “starting” levels before the increase began. In relation to the reference level indicator (532 cm on 16 January), this surge lasted from 20 hours in Warnemünde to 66 hours in Kołobrzeg.

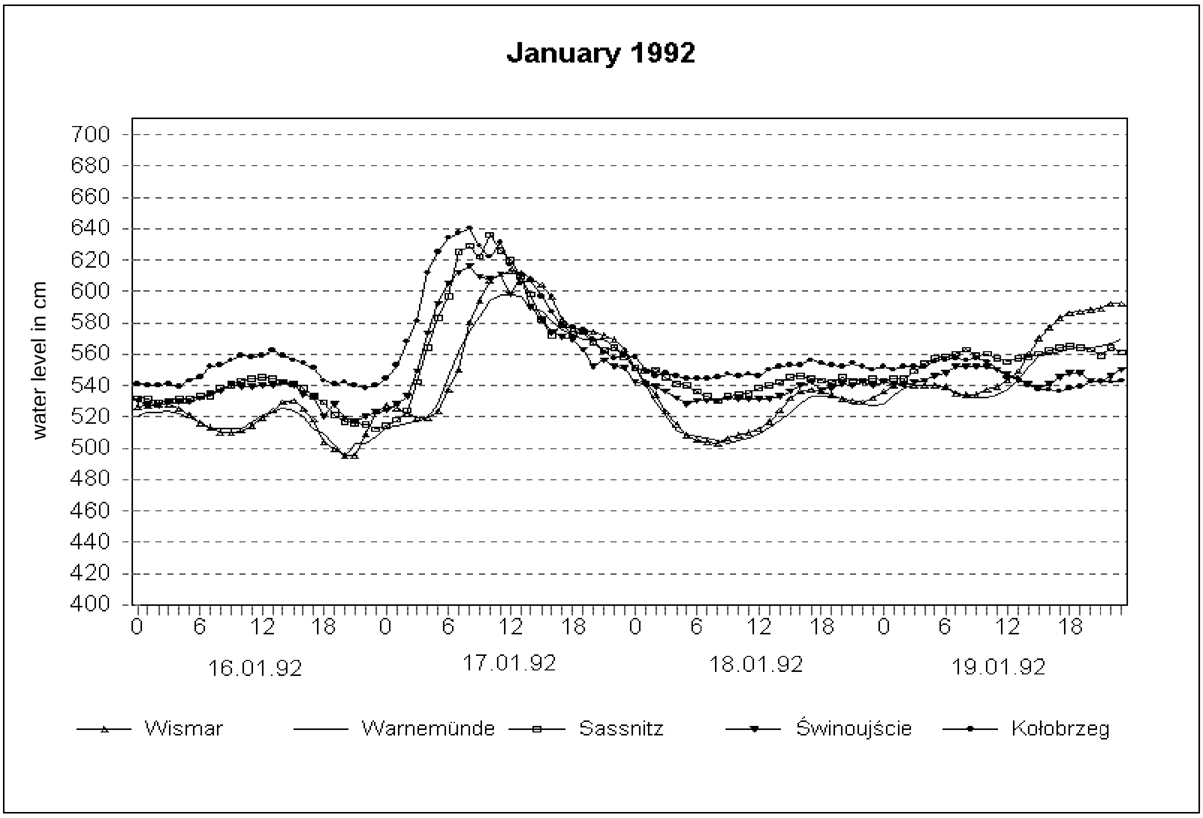

Fig. 6.11.2. Sea level changes during the storm surge of January 1992

6.12 <u>February 1993</u>

Meteorological situation

In the days between 19 and 23 February 1993, three surges of different intensity and duration were generated by stormy winds on the southern Baltic coasts.
On 19 February, a depression over the Norwegian Sea travelled across Scandinavia and, at about 03-06 UTC, entered the Baltic Sea near Stockholm, where it remained nearly stationary for a while, filling and moving very slowly eastwards. After the passage of the cold front, at about 03 UTC, a SW – W offshore gale developed which covered the entire southern region of the Baltic Sea. Due to a high pressure ridge which developed over Scandinavia, the gale soon veered (about 15 UTC on 19 February) and increased to a N – NW storm over the entire Baltic Sea (00 UTC on 20 February). It was not until about noon on the same day that the wind backed and decreased to about 6-5 Bft in the area (Fig. 6.12.1.).

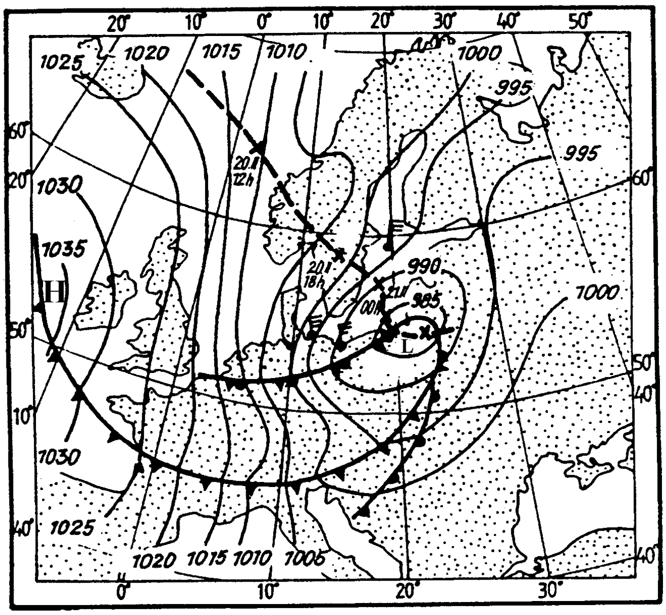

Fig. 6.12.1. Route of the stormy depression, pressure pattern and wind field over the Baltic Sea on 21 February 1993, 12 UTC

However, another active depression quickly moved in from the Norwegian Sea, tracking across Scandinavia towards the southeastern Baltic Sea where, between 00 and 09 UTC on 20 February, it slowed down and backed eastwards, reaching the Lithuanian coast around noon. Similar to the day before, a high pressure ridge over Scandinavia developed in the rear of this low. In the cyclonic wind system generated by the low, southwesterly to westerly winds of 6-8 Bft were recorded over the western and southern Baltic Sea in the afternoon of 20 February. In the night of 21 February, the winds developed into a northerly storm which soon, shortly past 09 UTC, veered NE and reached 7-9 Bft. The zone of NE storm first spread across the northern Baltic Sea and Baltic Proper and, towards noon on 21 February, also covered the western, southern and southeastern Baltic Sea. The northerly air flow brought cold Arctic air into the region, causing winds to become more gusty. In the late hours of 21 February, the pressure gradient weakened over Denmark, Kattegat and the western Baltic Sea, and the depression filled and moved towards Lithuania. In consequence, the storm over the entire southern Baltic Sea decreased to 8-6 Bft, and later 7-5 Bft, in the early hours of 22 February.
Late on the same day, the pressure gradient steepened again over the western Baltic Sea due to a ridge of high pressure spreading eastward from the British Isles. Northeasterly onshore winds strengthened again over the western parts of the coast and stayed there until the early hours of 23 February, after which they decreased slowly.

Hydrological response of the sea level

The described variation of the meteorological pattern resulted in a series of fluctuations of the water surface at the southern coasts of the Baltic Sea.
The first wind set-up was preceded by a decrease of sea levels about midday on 19 February. Water levels began to rise late on 19 February and rapidly reached their maxima, with extreme values not exceeding 590 cm, however.
When the northerly wind backed to alongshore directions and abated, water levels also fell slowly. The rate of decrease was soon accelerated considerably by a southwesterly storm which developed over the western and southern Baltic Sea in the afternoon and night of 20 February. The lowest value of nearly 460 cm was reached in Wismar; in the central part of the coast, sea levels oscillated around 500 cm (Fig. 6.12.2.).

The onset of the vehement N – NE storm that followed caused rapidly rising water levels, beginning in the central part of the coast: in about half a day the level rose by 1.2 m in Kołobrzeg, and 1.9 m in Wismar. The highest rates of increase, which were recorded in Wismar and Warnemünde, reached 35-37 cm/h. In the other areas of the coast, rates of 21-22 cm/h were recorded. The mean sea level was exceeded by 1.2-1.6 m during this surge. Culmination in the central part of the coast was observed between 12 and 15 UTC, with values of 630 cm in Kołobrzeg, 641 cm in Świnoujście, and 621 cm in Sassnitz; maxima in the western part were reached between 17 and 19 UTC, reaching 631 cm in Warnemünde and 656 cm in Wismar. Levels above 560 cm persisted for about 20-27 hours, after which the warning levels were maintained until 24 February. Based on the reference level indicator (520 cm on 21 February), this surge lasted from 29 hours in Wismar to 68 hours in Kołobrzeg.

The last major fluctuation in this series, which affected only the western part of the coast, began in the night of 22 February. Under the influence of NE onshore winds reaching gale force over the Kattegat and western Baltic Sea, the sea level began to rise around noon on 22 February and continued to rise until the early hours of 23 February. In Wismar, the maximum sea level was slightly above 585 cm, and in Warnemünde it was 565 cm, both at 00-01 UTC on 23 February. Then levels began to fall slowly.

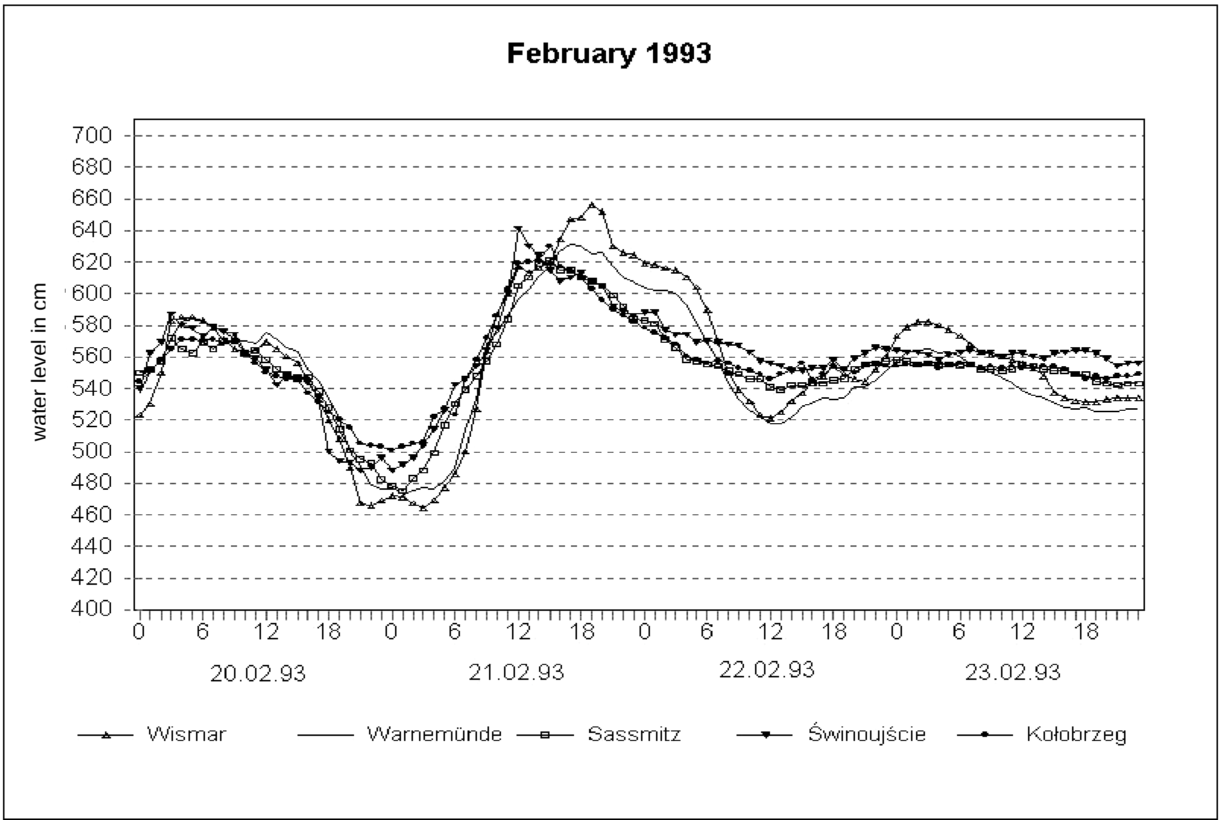

Fig. 6.12.2. Sea level changes during the storm surge of February 1993

6.13 January 1995

Meteorological situation

On 1 January, a high pressure ridge over the British Isles extended northeastwards across the Norwegian Sea and North Sea, and later over northern Scandinavia, while a large stationary depression (971 hPa at 00 UTC on 1 January) over central Scandinavia and the adjoining areas was filling. Its southern edge touched the western coasts of the southern Baltic Sea (Fig. 6.13.1). Strong offshore winds of 7-9 Bft set in on 1 January and continued until midnight, when they decreased and slowly veered N-NE, becoming stronger again around 03-06 UTC on 2 January. In the central part of the coast, the prevailing alongshore wind direction with a slight (westerly) onshore trend continued until the afternoon of 2 January.

The atmospheric pressure over Scandinavia grew steadily as the depression moved eastwards, and a N–NE air flow established itself over the whole Baltic Sea in the afternoon of 2 January. The fetch of the gale-force northerly winds now extended along the whole longitudinal axis of the Baltic Sea.

In the early hours of 3 January, the wind developed into a northeasterly storm of 9-10 Bft which first hit the central part of the southern Baltic coast (around midnight) and later (03-06 UTC) the western part. At about 09-12 UTC the storm decreased to a strong, and later moderate, wind of 7-5 Bft.

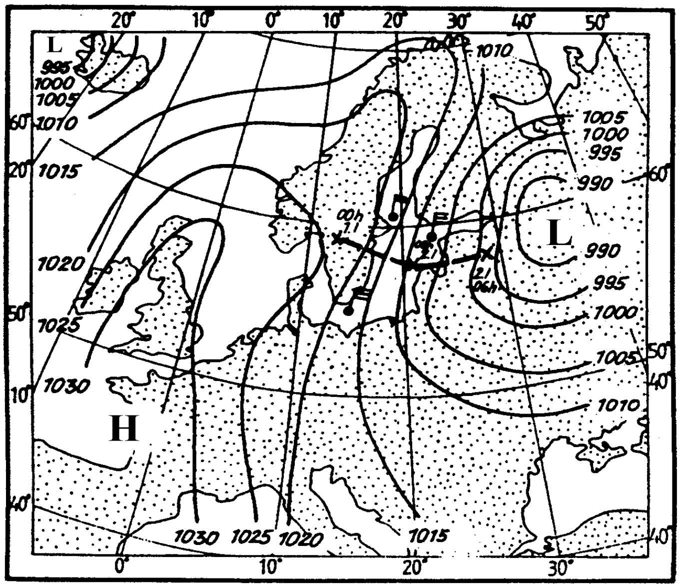

Fig. 6.13.1. Route of the depression centre from 00 UTC on 1 January to 06 UTC on 3 January 1995, pressure pattern and wind field over the Baltic Sea on 3 January, 06 UTC

Hydrological response of the sea level

On 1 January, slightly falling water levels were observed in the western part of the coast caused by moderate to strong offshore winds, which calmed towards midnight. The compensating rise of sea level began immediately, accelerated in the early hours of 2 January by the impact of a northerly gale. This first phase of the increase lasted about 9 hours, with levels of 580-600 cm reached around 05 UTC (Fig. 6.13.2.). The mean rate of increase was 8 cm/h, with a maximum of 20 cm/h reached between 6 and 7 UTC on 2 January.

In the central part of the coast, at the water gauges in Sassnitz, Świnoujście and Kołobrzeg, the set-up began in the early hours of 1 January, and levels continued to rise steadily until shortly after 00 UTC on 3 January. Culmination was reached at 615 cm in Sassnitz, 620 cm in Świnoujście, and 616 cm in Kołobrzeg. The maximum rate of increase, reached shortly before culmination, was 11 cm/h.

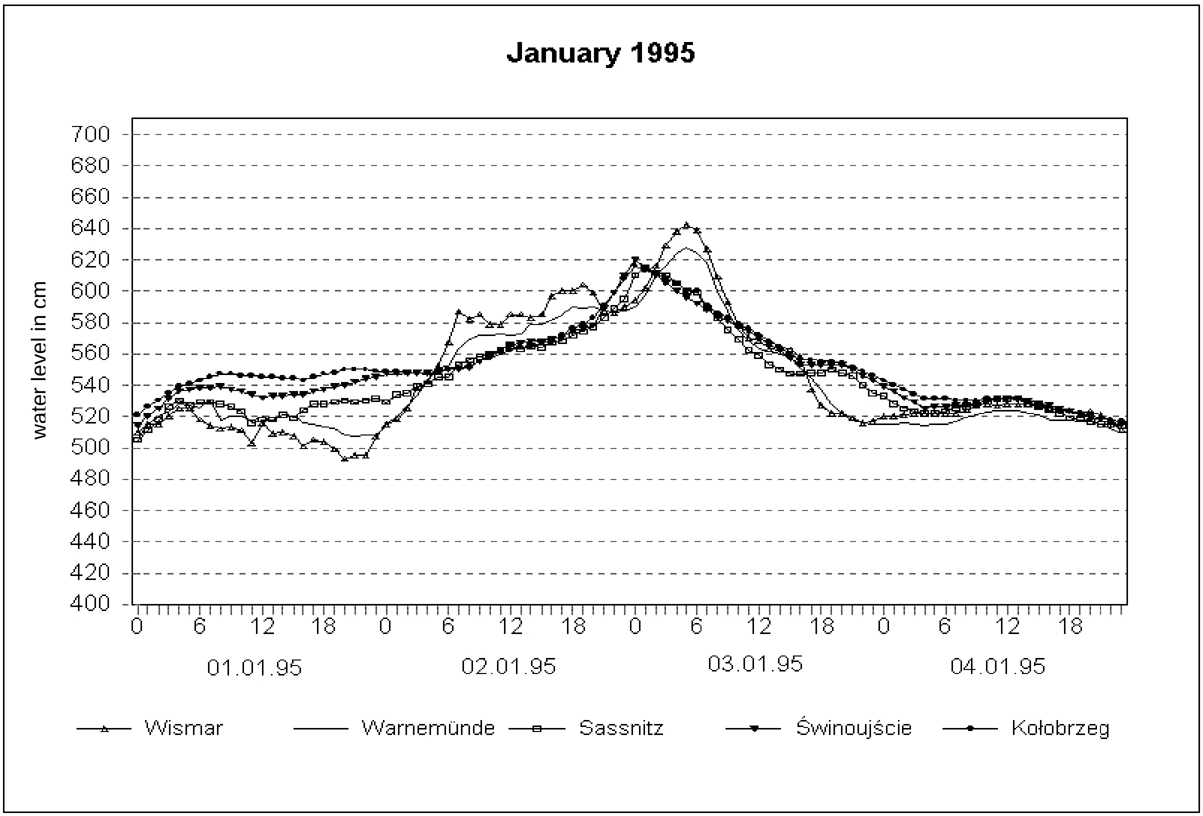

Fig. 6.13.2. Sea level changes during the storm surge of January 1995

The sea levels recorded by gauges in the western part of the coast remained at 580-600 cm, with minor oscillations, until about 05 UTC on 3 January, when somewhat higher culmination values were recorded: 642 cm in Wismar, and 629 cm in Warnemünde. Immediately after the culmination (05-06 UTC), sea levels fell continuously, though at a comparatively fast rate, to levels around 520 cm.

In the western part of the coast the warning levels persisted for about 32-34 hours, in the central part only about 26-29 hours.

In relation to the reference level indicator (541 cm on 1 January), the surge lasted from 37 hours in Wismar to 68 hours in Kołobrzeg.

6.14 April 1995

Meteorological situation

From the beginning of the month, the Baltic Sea was under the influence of vivid cyclonic activity. On 7 April, at about 00 UTC, a low-pressure centre of 997 hPa appeared north of the Shetland Islands and began tracking southeast, deepening rapidly. Within half a day, the centre extended from the Norwegian Sea to southern Scandinavia, and at about 15 UTC on 7 April, with an atmospheric pressure of 982 hPa, it entered the Baltic Sea near the island of Öland. Here it slowed down considerably and, meandering very slowly while its pressure continued to fall, reached the Lithuanian coast at about 03 UTC on 8 April (Fig. 6.14.1.).

Meanwhile, in the rear of the low over the Norwegian and North Seas, an anticyclone approached from the British Isles. The pressure gradient between the two centres steepened dangerously around noon on 7 April, especially over the central region of the Baltic Sea.

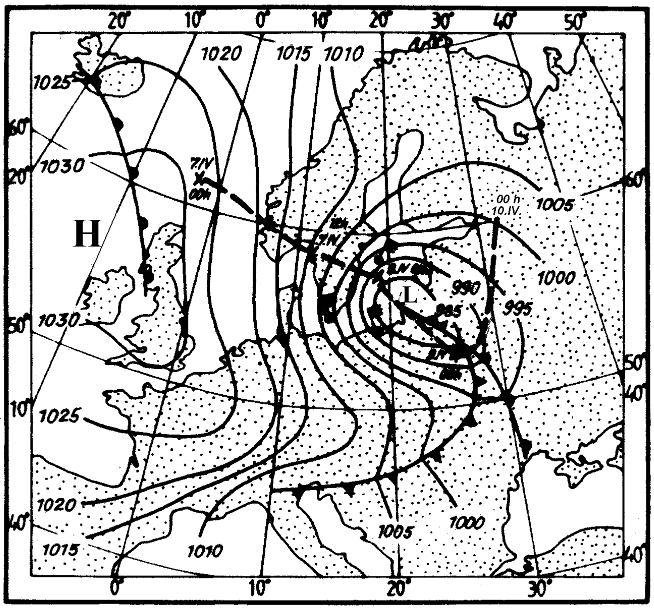

Fig. 6.14.1. Route of the depression from 00 UTC on 7 April to 00 UTC on 10 April 1995; pressure pattern and wind field over the Baltic Sea on 8 April 1995, 06 UTC

The steep gradient weakened only slowly in the course of 9 April as the low was slowly filling within 24 hours, from 03 UTC on 8 April to 03 UTC on 9 April, while it retreated to Lithuania, northeastern Poland and Western Bielorussia, from where its path backed NE – N. In the late hours of 9 April, the low was still well recognisable near Lake Ladoga (993 hPa), from where it travelled north-northwest across Finland. During its retreat, the depression left an elongated trough, so that the isobars over the Baltic Sea retained their north-south direction.
As the above pressure pattern developed on 7 April, the wind, which initially had been blowing from westerly directions with 5-7 Bft and later SW with 6-8 Bft, veered W – NW in the afternoon (in the eastern and central areas at first) and increased to 7-9 Bft. On 8 April, northerly and northwesterly winds continued to blow over the western, southern and southeastern Baltic Sea, whereas over the central and northern Baltic N – NE wind directions prevailed. The wind speed in the area varied between 7 and 9 Bft, reaching 10 Bft in gusts. The wind did not begin to abate until the late hours of 8 April, when the storm centre moved slowly towards Bielorussia.

Hydrological response of the sea level

The surge generated by the meteorological situation described above overlapped the already comparatively high (520-540 cm) water levels on the coasts. The surge rose relatively uniformly, beginning in the central area of the coast, but culmination was reached nearly simultaneously (about 17 UTC on 8 April) on the entire coast. Maximum water levels ranged from 608 cm in Sassnitz to 629 cm in Wismar. The mean rate of increase slightly exceeded 6 cm/h in Wismar and Warnemünde, and 3 cm/h in Świnoujście and Kołobrzeg (Fig. 6.14.2.).
The high water levels persisted for a long time: the warning levels were maintained for 12-25 hours.
In relation to the reference level indicator (541 cm on 7 April), the surge lasted from 27 hours in Wismar and Warnemünde to 54 hours in Kołobrzeg.

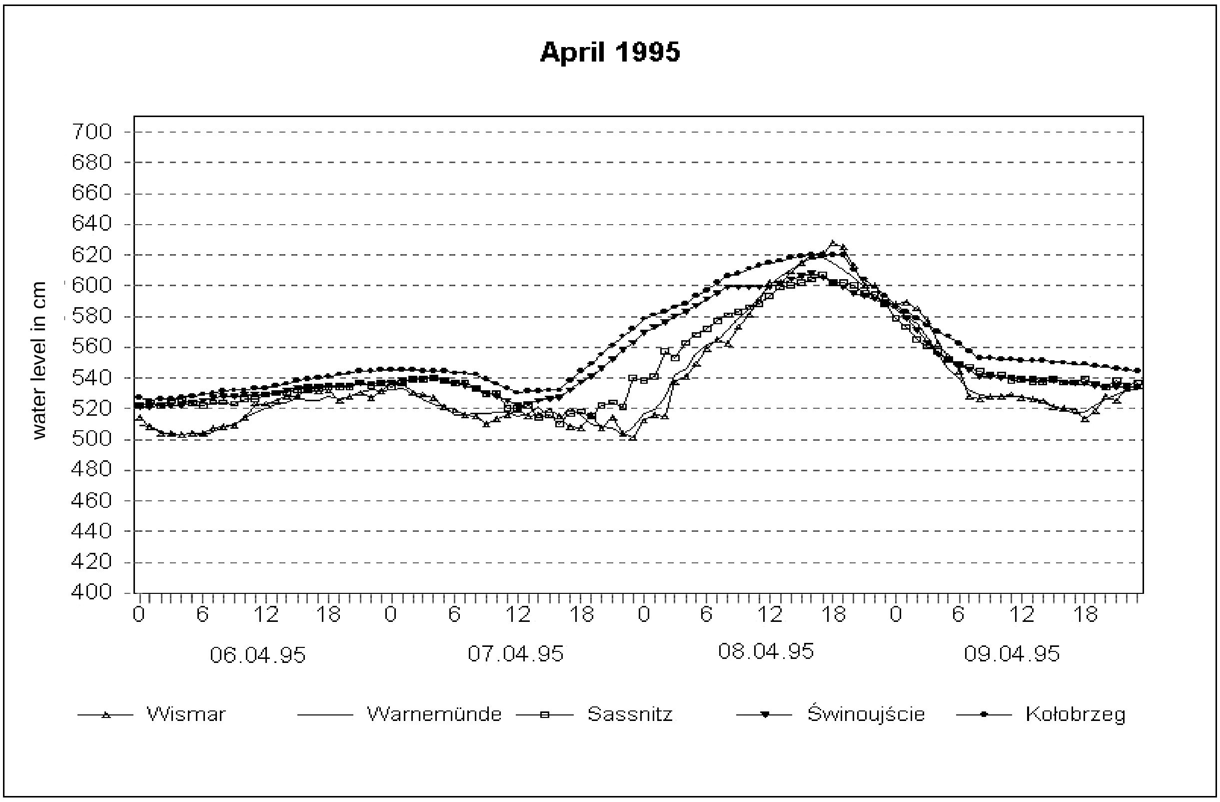

Fig. 6.14.2. Sea level changes during the storm surge of April 1995

6.15 November 1995

Meteorological situation

The strong northerly storm of 3-5 November 1995 affecting the whole area of the Baltic Sea was preceded by a weaker one on 1 November which, however, did not cause any serious rise of sea levels, especially in the western and central parts of the coast. This weaker storm was connected with a depression which formed south of Öland at 00 UTC on 1 November and travelled across the southern Baltic Sea in the following hours. Deepening very slowly, the depression reached the Lithuanian coast and continued on its east-southeast route towards the Bielorussian territory. Already in the late hours of 1 November, the depression was accompanied by strong NE–E winds covering the area of the southeastern Baltic Sea. Wind speeds reached 6-8 Bft, and up to 9 Bft in gusts. The wind veered in the early hours of 2 November, decreasing to moderate to light levels of 7-5 Bft (Fig. 6.15.1.).

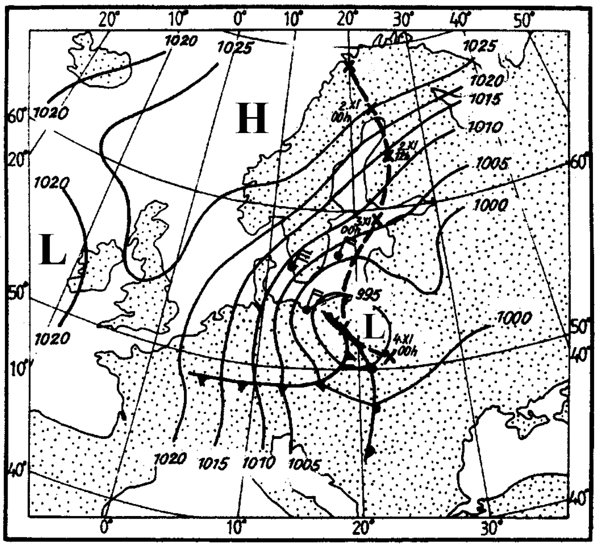

Fig. 6.15.1. Route of the depression (from 00 UTC on 2 November to 00 UTC on 4 November 1995) and pressure pattern on 3 November at 12 UTC with accompanying wind field over the southern areas of the Baltic Sea

However, a widespread flat depression with several weak centres remained over Scandinavia and the Baltic Sea. One of these centres, which was nearly stationary over Lappland, became more active, and at about 03 UTC on 2 November it began travelling slowly southwards along the eastern coasts of the Baltic Sea. Between 18 UTC on 2 November and 12 UTC on 3 November, the depression, still slowly deepening and meandering, reached the coast to the west of the Gulf of Gdańsk, moving southward. The depression was flat, with variable winds, but the pressure gradient over Scandinavia on the rear of the depression became menacingly steep, especially over Denmark, Kattegat, and the western Baltic Sea, where a strong northerly wind set in at about 09 UTC on 3 November and continued to increase. In the course of the following hours, a N-NE storm of 6-8 Bft travelled gradually eastward and covered the whole Baltic Sea, reaching 9 Bft in the western areas in the night of 3 November and in the morning of 4 November. Wind speeds recorded in Warnemünde reached 22 m/s, in Arkona 28 m/s, and in Świnoujście 19 m/s. The maximum wind speed recorded at the western coast during this night was nearly 35 m/s.

Hydrological response of the sea level

The described pressure pattern and wind conditions on 1-2 November, which threatened to generate a storm surge, did not cause a wind set-up on the western and central coasts. As the chief impact area of the storm was the southeastern coast, only an insignificant response of water levels was noticeable to the west of the Gulf of Gdańsk: scarcely 560 cm in Wismar at 00-04 UTC on 2 November. Only a short time before the beginning of the storm surge of 3-5 November, at about 00-06 UTC, the water level was only about 24-30 cm above mean sea level. Under the impact of the stormy northerly winds, water levels on the coast began to rise before noon on 3 November, first in the westernmost section of the coast – in Wismar and Warnemünde at about 06 UTC - and about 3-9 hours later in the central part (Fig. 6.15.2.). Water levels rose quickly, with maximum rates between 28 cm/h in the western part of the coast and 21 cm/h in its central section. The highest water levels were reached between 20 and 22 UTC in Wismar (702 cm) and Warnemünde (660 cm). Culmination in Sassnitz (637 cm) was reached at the same time at which also Świnoujście recorded a considerable peak of 652 cm, although the absolute maximum recorded by the Świnoujście gauge during this surge was as high as 669 cm and occurred about 7 hours later. The water gauge in Kołobrzeg measured 640 cm as its peak value on 4 November at 02 UTC.

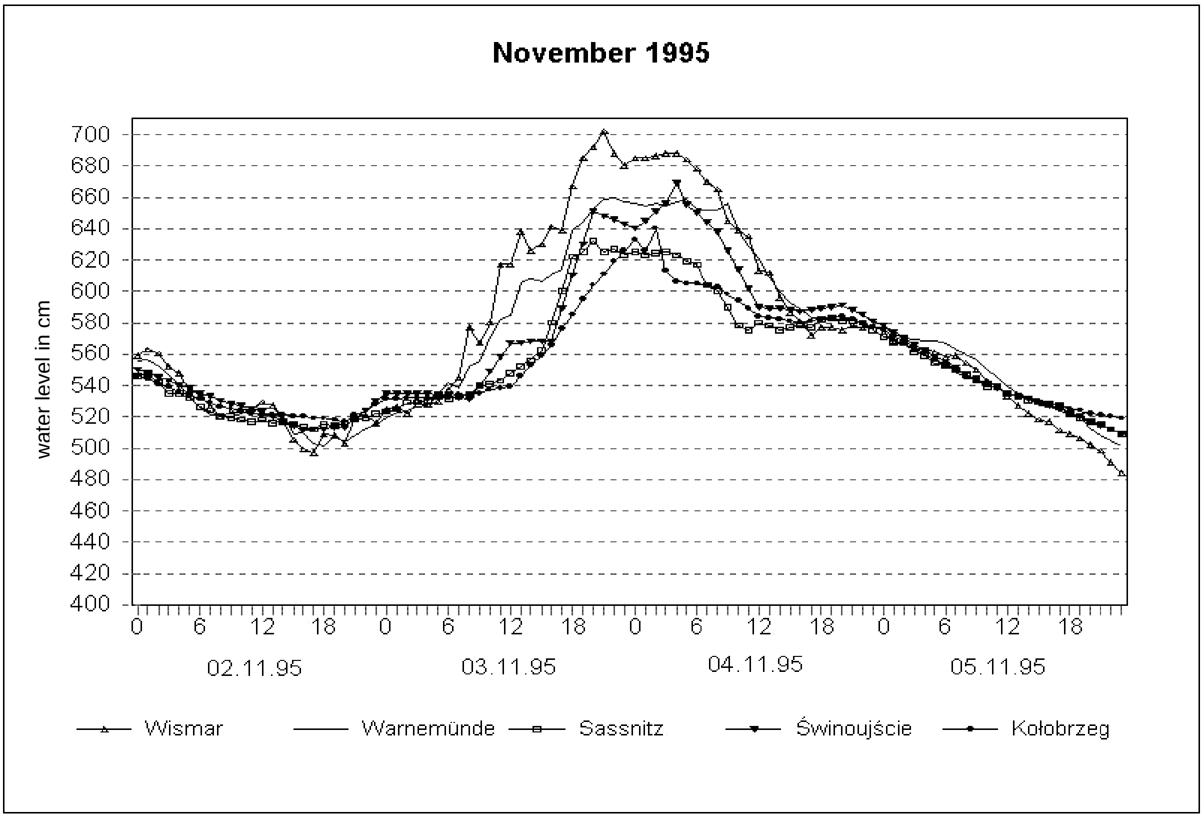

Fig. 6.15.2. Sea level changes during the storm surge of November 1995

During this surge, the mean sea level was exceeded by 1.6 to 2 m. High sea levels (values above the warning level) persisted for more than 24 hours, after which they decreased steadily to normal values. In relation to the reference level indicator (536 cm on 2 November) this surge lasted from 50 hours in Kołobrzeg to 55 hours in Warnemünde.
The variation curve of this surge has a shape which is characteristic of an onshore storm of long duration, stable direction and force: a comparatively steep, irregular increase curve (in Warnemünde 165 cm in about 14 hours), a quasi-flat maximum (plateau) with minor oscillations (in Warnemünde numerous oscillations of 5-10 cm amplitudes during approximately 12 hours), and a rather smooth slope of decay (about 85 cm in 8 hours) to a level that is remarkably higher than before the surge.

6.16 <u>April 1997</u>

Meteorological situation

On 9 -10 April, 1997, a weakening anticyclone travelled westwards from Central Europe and established itself over France and the British Isles (1034 hPa off Ireland), while low-pressure systems were moving from the Norwegian Sea in southeasterly direction, tracking across Scandinavia and the Baltic Sea. Some of the depressions soon filled as they moved south, while others emerged as secondary centres (Fig. 6.16.1.).

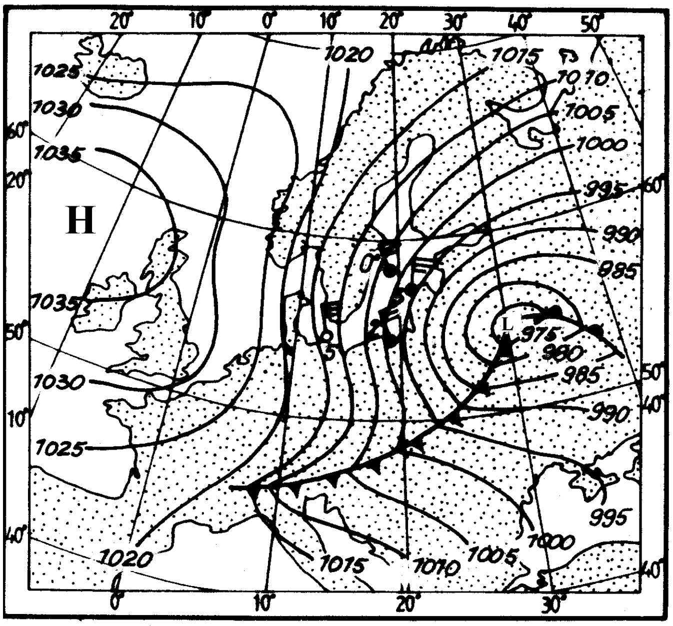

Fig. 6.16.1. Pressure pattern over Europe and wind field over the Baltic Sea on 11 April 1997, 18 UTC

On 10 April, successive troughs of low pressure moved across Scandinavia and the Baltic Sea, causing a southeastward flow of warm air and an inflow of cold Arctic air in their rear. In front of the trough and in its southern part, a westerly gale followed by a westerly storm of 8-9 Bft developed over the eastern North Sea, Kattegat and the Western Baltic Sea in the afternoon. Around midnight and in the early hours of 11 April, wind speeds in front of the advancing cold front occasionally exceeded 10-11 Bft over the western basins, with directions backing temporarily west-southwest. The storm was less severe in the eastern basins of the Baltic Sea.

Around 09 UTC on 11 April, the storm behind the cold front veered NW and reached 8 to 9 Bft in gusts. At about 15 UTC, a secondary cold front crossed the coast, with winds veering NNW – N and reaching 10 Bft in gusts. In the afternoon and during the night, the winds from northerly directions were still gusty but decreased gradually to 7-5 Bft in the early hours of 12 April.

In the course of 12 April, a high pressure ridge began to develop over Scandinavia, which was later destroyed by a southward moving low-pressure trough on 13 April. In front of the warm front which crossed the southern coast at 18 UTC on 13 April and became stationary until 16 April, SW winds increased to about 6-7 Bft between 09 and 15 UTC on 14 April. Wind directions on 14 April generally veered from WSW to W – NNW, but in the central part of the Southern Baltic Sea they oscillated locally over a rather wide range due to squall-like disturbances generated in the pre-frontal zone.

After the front had crossed the coastline at about 18 UTC on 14 April, the northerly air flow of force 6-7 Bft, which reached 8 Bft in gusts, established itself along the eastern edge of the high pressure ridge, which became stronger over Scandinavia. As the “old” quasi-stationary trough did not retreat (Fig. 6.16.2.), the pressure gradient zone with its northerly winds remained over Scandinavia and the Baltic Sea until 16 April, decreasing gradually.

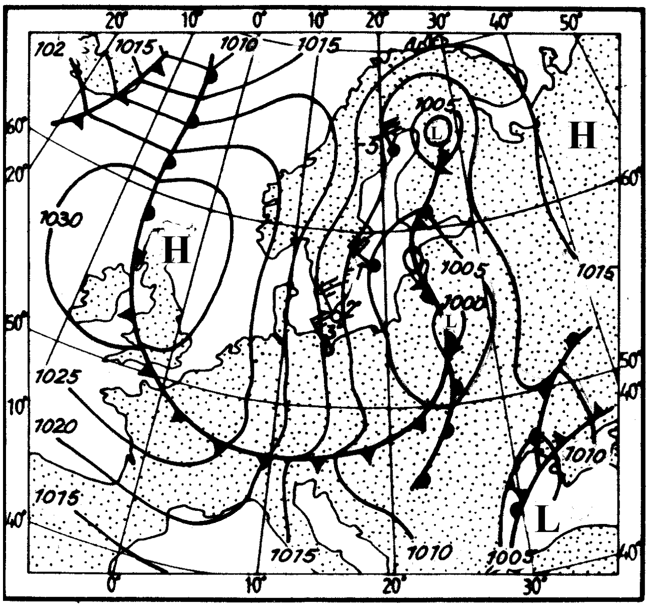

Fig. 6.16.2. Pressure pattern over Europe and wind field over the Baltic Sea on 15 April 1997, 06 UTC

Hydrological response of the sea level

On 10 April, water levels were close to the mean sea level. However, towards the end of the day and early on 11 April, in response to a vehement W – SW offshore and alongshore storm over the western basins, water levels in the area dropped to 472 cm in Wismar, and 484 cm in Warnemünde on 11 April at about 06 UTC. As the central parts of the coast were not affected by the direct impact of the SW storm, sea levels in Świnoujście and Kołobrzeg fell only slightly in the early hours of this day. As soon as the minimum had been reached shortly after 06 UTC, sea levels on the western coast began to rise following a rapid change of wind direction, with gale-force winds behind the cold front now blowing onshore (Fig. 6.16.3.). In the central part of the coast, the increase was slower and began about two to three hours earlier.

The warning level of >560 cm was first exceeded in Kołobrzeg at 11 UTC, Świnoujście at 14 UTC, Sassnitz at 16 UTC, Warnemünde at 19 UTC, and Wismar at 20 UTC on 11 April.

The maxima were reached very soon, between 17 and 23 UTC on 11 April. They exceeded the mean sea level by 1.0 -1.2 m and were as high as 620 cm in Wismar, 609 cm in Warnemünde, 604 cm in Sassnitz, 600 cm in Świnoujście, and 612 cm in Kołobrzeg.

The strongest surge dynamics were recorded by water gauges in the western part of the coast, where the culmination was recorded only 3 - 4 hours after warning levels had been exceeded. The maximum rate of increase was 52 cm/h in Wismar, but only half that rate was recorded in Warnemünde and Sassnitz, at 25 cm/h and 26 cm/h, respectively. The mean rates of increase were 19 cm/h in Wismar, 17 cm/h in Warnemünde, and 16 cm/h in Sassnitz.

In the Pomeranian Bight and farther to the east, the surge dynamics were less pronounced although warning levels in this area were exceeded earlier than in the western parts of the coast. The increase was slower, with culmination in Świnoujście reached 5 hours after warning levels had been exceeded, and in Kołobrzeg after as much as 10 hours. The maximum rate of increase was 25 cm/h in Świnoujście and 22 cm/h in Kołobrzeg, with a mean rate of increase of 11 cm/h and 6.4 cm/h, respectively. Sea levels remained above 560 cm for 22 hours in Świnoujście, and 27 hours in Kołobrzeg. The decrease was smoother than that recorded by water gauges in the western part of the coast.

The second rise of sea levels during these five days was preceded by a brief drop of water levels on the western coasts in the afternoon of 13 April due to an offshore SW gale, with the

level at Wismar dropping as low as 452 cm. Levels soon began to rise again, but with a very irregular pattern caused by the rather variable onshore NW – N storm. The amplitudes of sea level oscillations were greater in the west, although the maximum in this section of the coast was recorded at Świnoujście, where 584 cm was reached in the night of 16 April. Culmination in Kołobrzeg, Sassnitz, Warnemünde and Wismar was observed between 9 and 11 UTC on 15 April, with values of 568 cm, 561 cm, 570 cm and 582 cm, respectively.
In relation to the reference level indicator (521 cm on 11 April) this surge lasted from 112 hours in Kołobrzeg to 120 hours in Warnemünde.

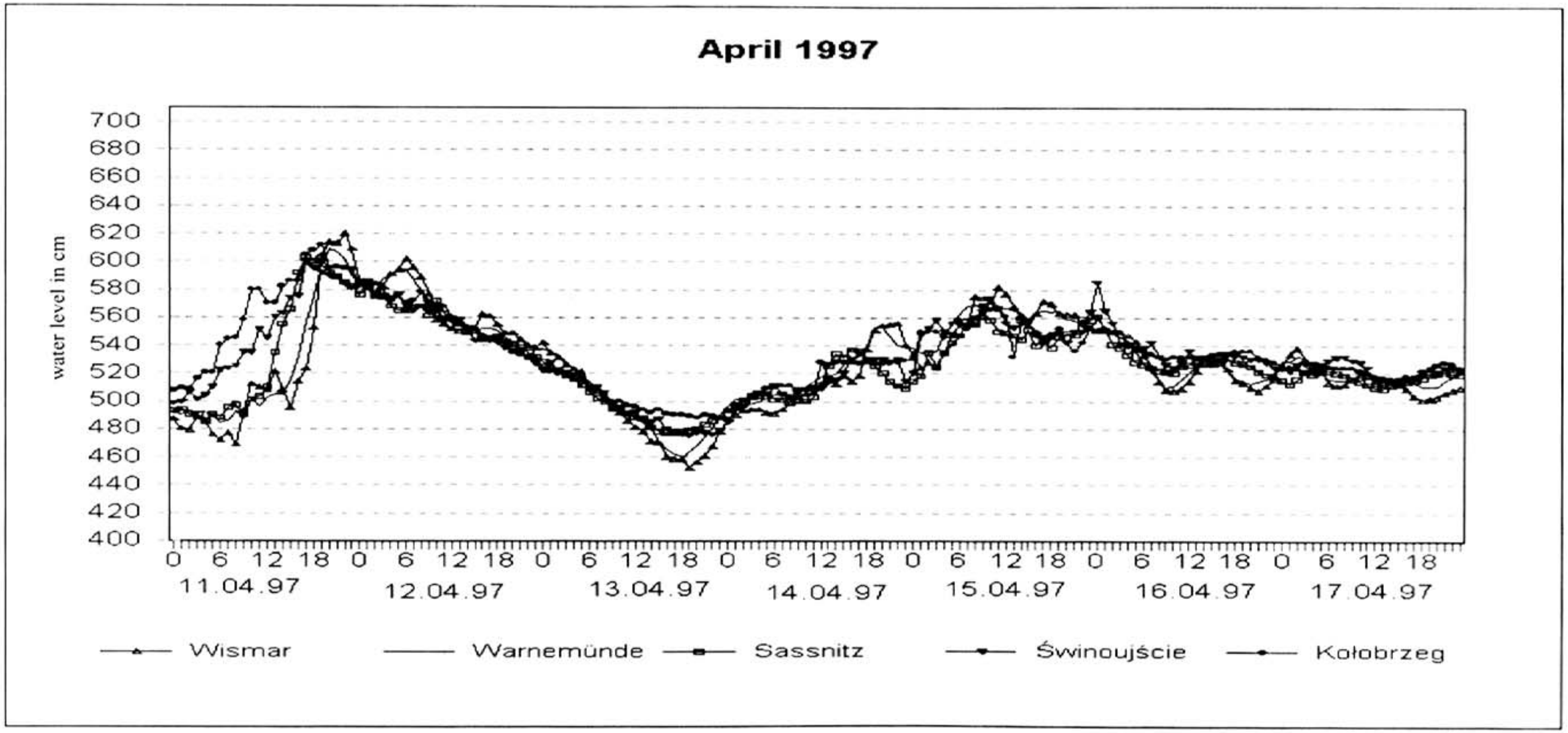

Fig. 6.16.3. Sea level changes during the storm surge of April 1997

6.17 January 2000

Meteorological situation

On 15 - 17 January 2000, the three days preceding the storm surge, northwesterly air flow prevailed over the North and Baltic Seas. This flow was generated by a wide, quasi-stationary high-pressure system over the northeastern North Atlantic. Atmospheric pressure in the centre of this high, which was located off Ireland, exceeded 1045 hPa. Along the eastern edge of the anticyclone, successive low-pressure troughs from the Arctic waters northeast of Scandinavia tracked S – SE across the Baltic Sea towards the Russian plains.
On 17 January, a zone of steepening pressure gradient formed over the western basins of the Baltic Sea and soon spread eastwards. The wind veered N – NE and increased to gale force 7 – 8 Bft and locally 9 Bft. This development continued on 18 January until, in the early hours of 19 January (Fig. 6.17.1.) the wind abated slightly, but not below 4 - 6 Bft.
On 20 January, as successive low pressure troughs travelled southeast across Scandinavia and the Baltic Sea towards Bielorussia, the wind backed NW – W and increased again to 6 – 7 Bft towards evening,
The cold front connected with this trough first crossed the central and eastern parts of the coast, i.e. Kołobrzeg and Świnoujście, shortly before midnight in the night of 21 January and, some hours later, between 03 and 05 UTC on 21 January - the regions of Warnemünde and Wismar. After the passage of the cold front the wind veered N - NE, increased to 7-9 Bft and became gusty again due to below-zero temperatures of the intruding Arctic air (Fig. 6.17.2.). The storm lasted until the afternoon of 21 January, when the gradient weakened and the wind decreased to 5-6 Bft locally, first beginning in the western part of the coast.
Soon after midnight the wind backed W – SW and decreased gradually.

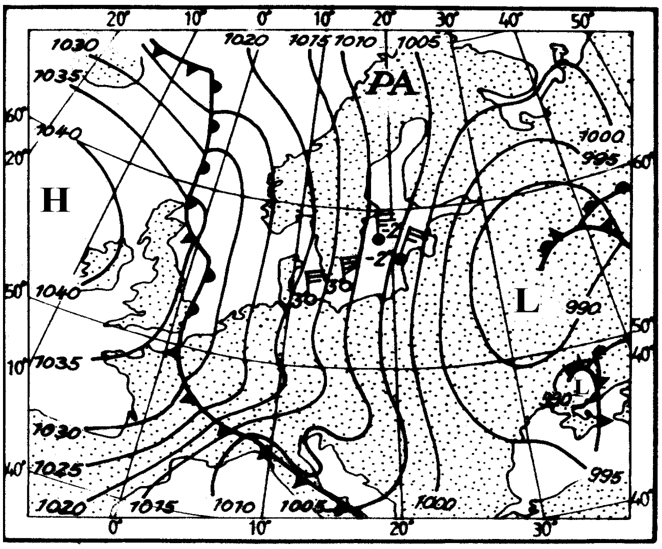

Fig. 6.17.1. Pressure pattern over Europe and wind field over the southern Baltic Sea at 00 UTC on 19 January 2000 – an example of the long-lasting northerly air flow over Europe which often causes wind set-up along the southern coast of the Baltic Sea

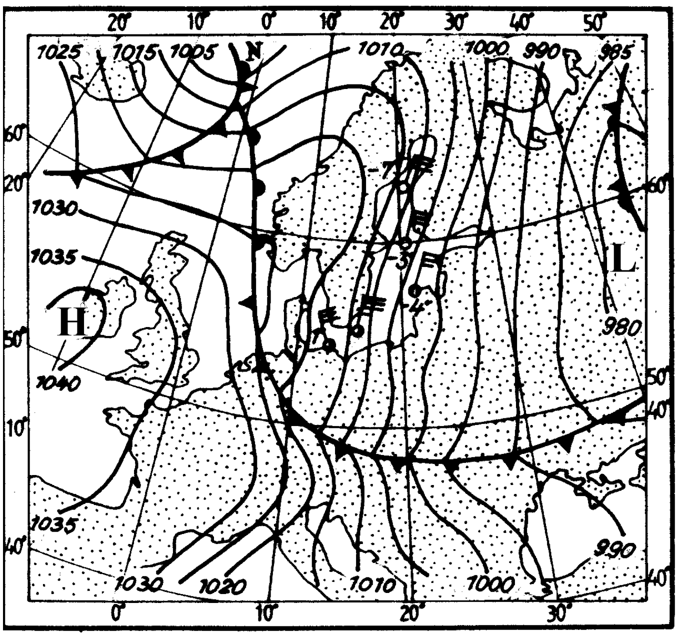

Fig. 6.17.2. Pressure pattern over Europe and wind field over the southern Baltic Sea at 12 UTC on 21 January 2000

Hydrological response of the sea level

On 17 January, under the impact of an onshore storm with a nearly constant wind speed, sea levels began to rise along the entire coast: first at the eastern water gauges (Kołobrzeg before midnight) and shortly later, at about 04 UTC, in Warnemünde, and about 06 UTC in Wismar. While the eastern water gauges recorded a rather uniform sea level increase, sea levels farther west showed major oscillations which were caused by a pulsation of the pressure gradient over this area and by the more complicated coastline.
The increase lasted about two days. Culmination was reached at 19 UTC on 18 January in Kołobrzeg (600 cm), three hours later in Świnoujście (600 cm) and Sassnitz (590 cm); the maxima in Warnemünde (601 cm) and Wismar (607 cm) were recorded at 02 UTC on 19 January. Water levels then began to fall rather rapidly in the late hours of 19 January, supported by the W – SW gale blowing alongshore and slightly offshore. Especially in the western coastal area, the minima dropped as low as 483 cm at about 13 UTC on 20 January. The sinking of sea levels in Kołobrzeg lasted only until about 06 UTC, and levels at this gauge did not drop below 515 cm.
Shortly after noon on 20 January, a new phase of rising sea levels began, forced by a W – NW gale in the low pressure trough, which changed to a N – NE storm around midnight on 21 January. This time the rather sharp maximum was reached between 12 UTC and 14 UTC in Kołobrzeg, at 596 cm, Wismar at 599 cm, Świnoujście at 597 cm, and Warnemünde at 589 cm. Only the maximum at Sassnitz, at 581 cm, was delayed by about 6 hours. During these 6 days, a rather high reference level indicator of 545 - 559 cm reflected the characteristic conditions on the southern Baltic Sea coasts. Calculated values varied from 529 cm in the morning of 17 January to 551 cm in the morning of 22 January.
The first surge lasted 50 - 67 hours, and the second one 32 - 37 hours.
The mean rate of increase was not very high, fluctuating around 2 cm/h on 17 and 18 January, and around 3-5 cm/h on 20 and 21 January. In some oscillations, however, especially at the western coast, the sea level rose in a very unsteady way: the initial “jump” in Wismar, between 06 and 09 UTC on 17 January, exceeded 16 cm/h, and a similar increase rate was recorded on 18 January between 10 and 13 UTC; the in-between oscillations were smaller.

Characteristic features of both of these two storms which led to the high water levels described above were the direct impact of an onshore wind blowing rather steadily from northerly directions and their long fetch, although wind speeds of 9 Bft were reached only occasionally.

The response of the coastal water was nearly uniform along the entire southern coast, and culmination values occurred nearly simultaneously. There was no shift of phase as is usually observed when a disturbance is accompanied by a sharp wind shear (e.g. in a low-pressure centre moving along the coast).

Referred to the reference level indicator for 17 January (537 cm), these two surges lasted from 50 hours in Wismar to 68 hours in Kołobrzeg, and in relation to that for 20 January (535 cm) from 31 hours in Wismar to 37 hours in Kołobrzeg.

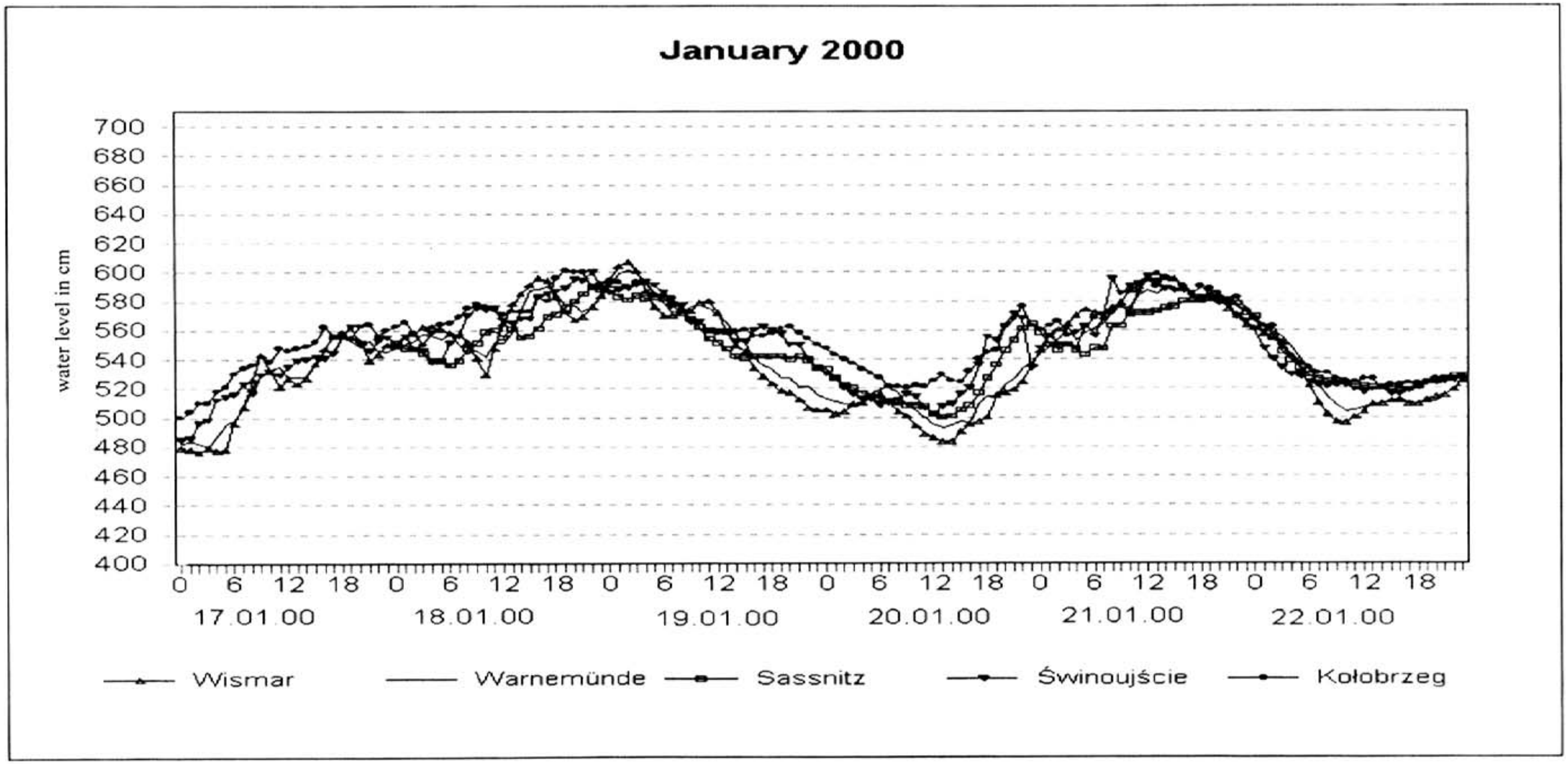

Fig. 6.17.3. Sea level changes during the storm surges of January 2000

CONCLUSIONS

Since the beginning of the verified observation series in 1950/51, the number of storm surges per decade has grown from 13 in the 1950s through 15 and 22 in the next two decades to 34 in the 1980s. In the last decade of the 20th century, the number of surges was hardly lower, at 32.

In the two periods studied, i.e. 1950 – 1975 and 1976 – 2000, the mean annual (seasonal) distributions differ only in the month of maximum occurrence: in the first 25-year period, storm surges were most frequent in November (about 27 % of storm surge events), while in the second period from 1976 –2000 the maximum shifted toward January, with about 29 % of all storm surges. The storm surge seasons in 1950 – 1975 were also found to be shorter. The first seasonal storms occurred as late as September (about 2 %), and the last storm events were recorded in March, though with a high frequency of 8 %.

A characteristic feature of the monthly frequency distribution of storm surges is the absence of storm surge events in May, June, and July.

The storm surge season in the period 1976 – 2000 lasted from the last days of August (frequency of 1 %) to April, with about 3 % of all annual storm surges.

Summarising the above, it can be said that, in comparison with the earlier period reviewed in the present study, the probability of storm surge flooding has about doubled towards the end of the century.

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TABLE INDEX

ACRONYMS

BSH	Bundesamt für Seeschifffahrt und Hydrographie – Federal Maritime and Hydrographic Agency of Germany
HH	Land survy datum of Mecklenburg/Vorpommern
IMGW	Instytut Meteorologii i Gospodarki Wodnej – Institute of Meteorology and Water Management
MBLU	Ministerium für Bau, Landesentwicklung und Umwelt Mecklenburg-Vorpommern
NATO	North Atlantic Treaty Organisation
NN	Land survy datum of Schleswig/Holstein and Poland
P	Probability
PN	Gauge datum
T	Intervals of recurrence
UTC	Universal Time Coordinated
WMO	World Meteorological Organization

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