

Water level fluctuations in the Odra River mouth area in relation to passages of deep low-pressure systems

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Abstract

The Odra River mouth area is affected by storm surges caused by passages of deep low-pressure systems over the Baltic Sea. The surges are the result of wind action and changes in atmospheric pressure at the sea surface. The two effects may be additive, in which both factors increase or decrease the sea level on the coast, or they may be non-additive, where one factor increases the sea level and the other decreases it. This paper discusses the role of the wind field and changes in atmospheric pressure in the duration and extent of storm surges in the Odra River mouth area.

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INTRODUCTION

The sea level of the southern Baltic shows substantial variability, which results from the overlap of various types of periodic oscillations and non-periodic fluctuations. The latter, particularly those related to passages of deep and intense low-pressure systems that may produce 1.0-2.0 m high local storm surges and 0.5-1.5 m deep storm falls, are most dangerous for navigation on the water and for the stability of the coastline and beaches. The fluctuations in question are caused by wind action and changes in atmospheric pressure at the sea surface, the so-called baric wave, as has been shown by Wiśniewski et al. (2005). Wind and waves may be additive in their effects, i.e., they act in concert to increase or decrease the sea level on the coast, or their effects may be non-additive, as when one factor produces a sea level increase, while the action of the other results in a decrease.

The timing of wind-caused storm surge or storm fall is directly related to wind velocity, duration and direction. In the Pomeranian Bay, those sea level fluctuations vary within ± 40 cm (Wiśniewski et al. 2005). Additionally, prolonged stationary weather systems over the Baltic Sea result in changes in its water volume and may cause ± 50 cm changes in sea level, as reported by Dziadziuszko and Jednorąg (1987). However, gauge readings show that water level fluctuations during storm surges and falls in the coastal zone can be much more extensive. These result from changes in the air pressure at the sea surface during the passage of a low-pressure system. Such changes generate a sea surface deformation, or a baric wave, with its positive phase inside the low and its negative phase outside it. The wave is like a cushion of water under a depression that moves together with it. It should be noted that the effect of pressure on the sea surface may greatly exceed the impact of wind (Wiśniewski et al. 2005).

The pattern of water level fluctuations also depends on the velocity of displacement of a low and on the air pressure drop at its center (Δp). Deep (below 980 hPa) lows moving at a high speed produce significant fluctuations in sea level, which are mainly the result of the baric wave. The wind effect is less pronounced due to the relatively short duration of wind from a given direction. The wind effect is far greater during passage of shallow (above 980 hPa at the center) and slow (less than 30 km per hour) low-pressure systems.

On the Polish coast, the dynamic effects of the wave caused by changes in air pressure are more evident in the eastern part of the low, whereas increasing wind speeds are observed in the western part. A storm surge scenario depends also on the trajectory of the low and its distance from the coast. As reported by Wiśniewski (1991), the most frequent direction of movement of depressions over the Baltic Sea is from WSW to ENE.



Fig. 1. The Odra river mouth area.

The Odra River mouth, situated in the southern Baltic Sea (Fig.1), has a very low hydraulic slope. When undisturbed, free water discharge from the Odra into the sea is observed (the average water level): the water level difference between Pomeranian Bay (Świnoujście) and Szczecin Lagoon (Trzebież) is 8 cm, with the difference between levels in Świnoujście and Szczecin being 14 cm (Dziadziuszko and Sztobryn 1997). As a result of the very low gradient of the Lower Odra channels, water level changes in this section are strongly affected by changes in the water levels in Szczecin Lagoon and Pomeranian Bay. During strong storm surges, when the sea level in the Bay is higher than in the Lagoon, the Bay's brackish water enters the Lagoon and raises the water level both there and

in the Lower Odra channels. Under these circumstances, the wind-driven water backflow in the Odra river mouth may penetrate as high upriver as Gozdowice, as shown by Buchholz (1990). The effect is particularly pronounced during autumn and winter storm surges under very strong northerly winds. In contrast, the effect of the instantaneous Odra discharge on water levels in the river's mouth area is of less importance because, even during Odra flood events, the water level increases by only a few centimetres as the flood wave enters the Szczecin Lagoon (Buchholz 1990).

In recent years, storm surges along the southern coast of the Baltic Sea have been the focus of numerous studies. The effect of passages of deep low-pressure systems on sea level fluctuations was described in studies by Maliński (1965), Majewski et al. (1983), Malicki and Wielbińska (1992), Wiśniewski (1997), and Sztobryn and Stigge (2005). The influence of atmospheric dynamics on water levels in the Szczecin Lagoon and the Lower Odra River channels was presented in studies by Buchholz (1989, 1990), Robakiewicz (1993), Ewertowski (1996, 2000), Meyer and Ewertowski (1997), and Wiśniewski et al. (2005). In the present study, storm surges in the period from 30 October 2001 to 31 December 2004 were studied in order to estimate the impact of wind action and changes in atmospheric pressure on the duration and extent of storm surges

in the Odra river mouth area. A second objective was to separate typical scenarios of storm surges in the Odra river mouth area.

METHODOLOGY

A total of 28 episodes of a dynamic increase in water level in the Pomeranian Bay or Szczecin Lagoon, above the warning or alarm states, during the passage of a low-pressure system over the Baltic Sea were included in our analyses. Instances of very low water levels in the Pomeranian Bay also were included. Initially, water level fluctuations in the Odra river mouth area were analysed in relation to characteristics of a corresponding atmospheric low (trajectory, velocity of passage, pressure in the centre) and local wind conditions (direction and velocity). The effect of instantaneous water level in the lower Odra branches was taken into consideration as well. Subsequently, the impact of the wind and baric wave on the duration and extent of the storm surge in the Pomeranian Bay, Szczecin Lagoon and the lower Odra branches was estimated. On that basis, typical scenarios of water level fluctuations in the Odra mouth area were identified.

The data were obtained from routine readings of tide gauges located in the Odra river mouth area, including the southern part of the Pomeranian Bay, the Szczecin Lagoon, and the downstream reach of the Odra. Data on the water level series and weather conditions were obtained from the Harbour Master's Office in Szczecin, the Regional Board for Water Management in Szczecin, and publicly available databases of the Institute of Meteorology and Water Management in Poland and Bundesamt für Seeschifffahrt und Hydrographie in Germany. Earth surface air pressure distributions were obtained from the German Weather Service.

In Świnoujście the warning and alarm states are 560 cm NN and 580 cm, respectively; the respective levels in Trzebież are 540 cm NN and 560 cm, and they are 560 cm NN and 580 cm in Szczecin. Further upstream along the Odra, the alarm states are as follows: 570 cm in Gryfino, 620 cm in Widuchowa, and 410 cm in Gozdowice (Fig. 1).

TYPICAL SCENARIOS OF WATER LEVEL FLUCTUATIONS IN THE ODRA RIVER MOUTH AREA DURING STORM SURGES

A wind- and baric wave-caused storm surge, high river levels (22–26 November 2001)

A substantial storm surge on the southern Baltic coast, lasting from 22 to 26 November 2001, was the result of a passage of a deep low-pressure system that

moved eastwards from the North Atlantic over the Scandinavian Peninsula, the central part of the Baltic Sea, and further to the east (Fig. 2A). Initially, on 22 November, the water level dropped along the Pomeranian Bay coast (Fig. 2B). In Koserow, a minimum of 478 cm NN was recorded at 2 a.m., in Świnoujście, a minimum of 506 cm, recorded at 8 a.m., was mainly the result of WSW

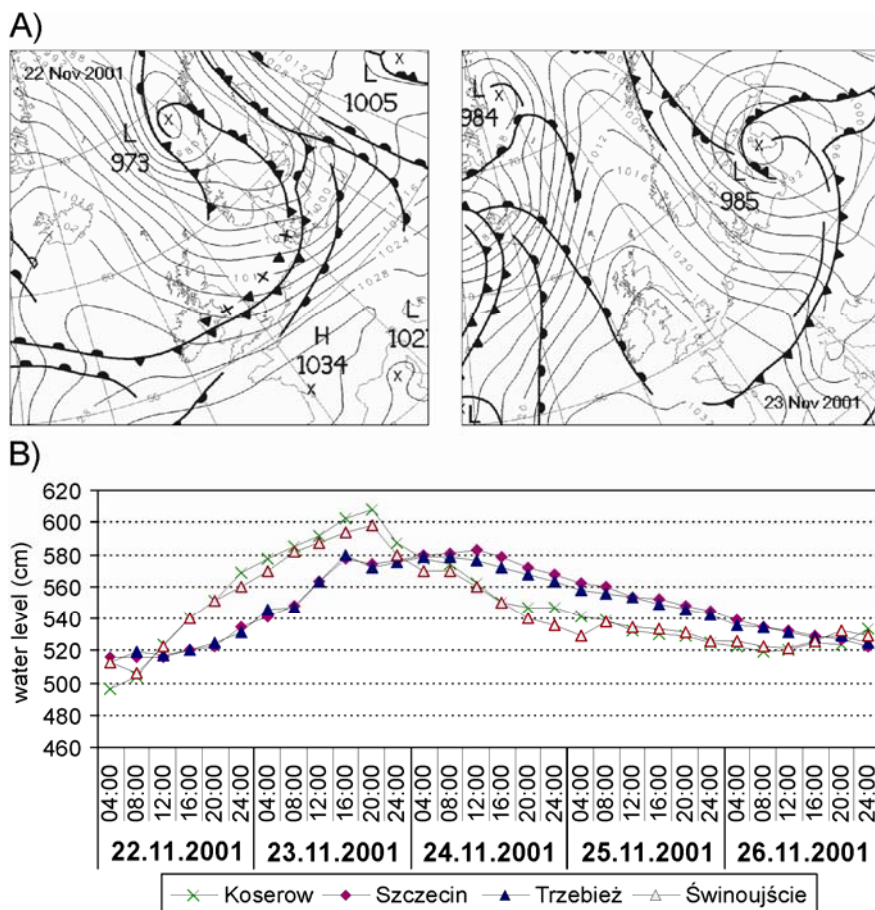


Fig. 2. The synoptic situation: A – after <http://www.wetterzentrale.de/topkarten/fsfaxsem.html> and water levels in the Odra River mouth; B – area during the 22-26 November 2001 storm surge.

winds. Subsequently, sea level began to rise rapidly to reach a maximum on 23 November as a result of the low-pressure centre's fast shift over the central Baltic (985 hPa in the centre) and northerly winds. In Koserow, a maximum of

609 cm was recorded at 6 p.m., the maximum in Świnoujście, recorded at 8 p.m., was 598 cm, under NW winds. Then, the pressure low shifted eastwards and, starting on 25 November, winds from the southern sector were observed. This situation resulted in a decrease in the water level along the Pomeranian coasts during the next few days.

During the discussed storm surge, the Szczecin Lagoon stations showed much weaker water level fluctuations that followed, with a time lag, changes in the sea level (Fig. 2B). From 22 to 23 November, a constant increase in the Lagoon water level (by 70 cm) up to the maximum (e.g., 580 cm in Trzebież at 4 p.m.) was observed. As a result of the 3-day-long period of winds from the WNW to NNW, alarm levels remained for more than one day. Beginning on the afternoon of 24 November, the water level was observed to drop slowly, down to 525 cm on 26 November.

The impact of this low-pressure system was also recorded by the gauges located in the downstream Odra reach. The maximum water level in Szczecin (western Odra branch), 583 cm (on 24 November noon), occurred with a time lag of 20 hours relative to the Trzebież water level maximum. In Gryfino, the maximum water level of 590 cm (a 55 cm increase) was recorded also on 24 November. In Widuchowa, the water level increased by 52 cm to reach 600 cm on 24 November. In Gozdowice, the effect of the storm surge was negligible (levels of ca. 330 cm). It is notable that the storm surge in the Lower Odra channels, which lasted longer than 3 days, was caused not only by northerly winds, but also by the accumulation of Odra waters remaining from the previous November storm surge.

A short-lived storm surge (01–04 January 2002)

Between 01–04 January 2002, a fast moving low-pressure system from the Norwegian Sea passed over the central part of Scandinavia and the central Baltic Sea, then progressed farther east, and eventually moved back over the North Atlantic, inducing storm surge on the southern coasts of the Baltic (Fig. 3A). On 1 January, the location of the system (989 hPa in the centre) over the Norwegian Sea and the development of a high-pressure system (1039 hPa in the centre) over western Europe resulted in WSW winds along the Pomeranian Bay coasts and in a water level drop to 449 cm at 8 p.m. (Świnoujście). The next day, the fast movement of the low over the central Baltic (992 hPa, 86 km h⁻¹) and a change in the wind direction (NW–NNE) resulted in a rapid increase in the water level up to 604 cm in Świnoujście at noon (Fig. 3B) and 624 cm in Koserow at 2 p.m. Later on, the northward shift of the low and the development of a high (1042 hPa in the centre) over the southern Baltic generated the system

of SW–S winds and resulted in a rapid drop in the sea level to 482 cm (Świnoujście) during the night of 3 January (negative phase of the baric wave).

During the January 2002 storm, the effect of the rapid shift of the low was negligible in the Szczecin Lagoon and in the Lower Odra channels (Fig. 3B). The high water levels both in the Lagoon (warning levels) and along the downstream Odra reach (warning levels in Szczecin and alarm levels in Gryfino and Widuchowa) resulted from the previous wind-driven backflow that was observed in December 2001.

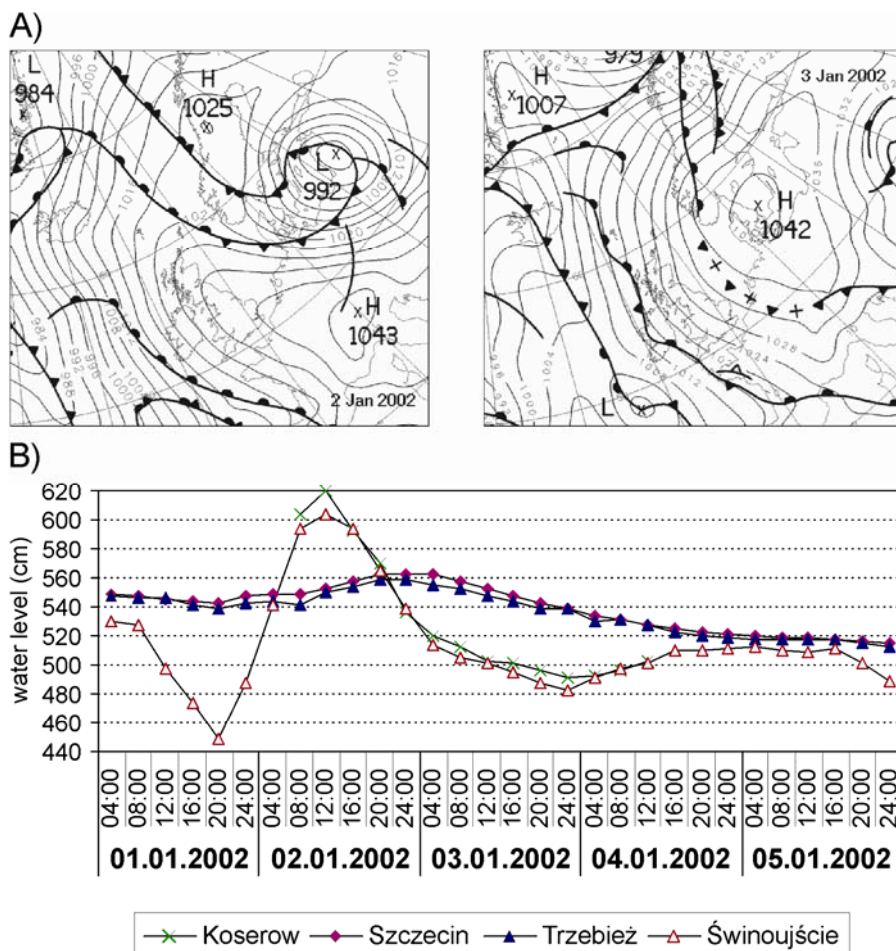


Fig. 3. The synoptic situation: A – after <http://www.wetterzentrale.de/topkarten/fsfaxsem.html> and water levels in the Odra River mouth area; B – during the 01-04 January 2002 storm surge.

A wind-caused storm surge (29 September–2 October 2004)

Between 29 September and 2 October 2004, another low-pressure system with 1007 hPa in the centre passed over the Jutland Peninsula, along the southern Baltic coasts, the Gulf of Gdańsk, and proceeded farther east (Fig. 4A). Along the Pomeranian Bay, the low-pressure system generated 6°B force south-westerly winds. This shallow and slow-moving low resulted in an increase and then a decrease in the sea level at the Pomeranian coasts. In Świnoujście, a maximum sea level of 576 cm was recorded during the night of 29 September. High sea level remained for half a day (Fig. 4B).

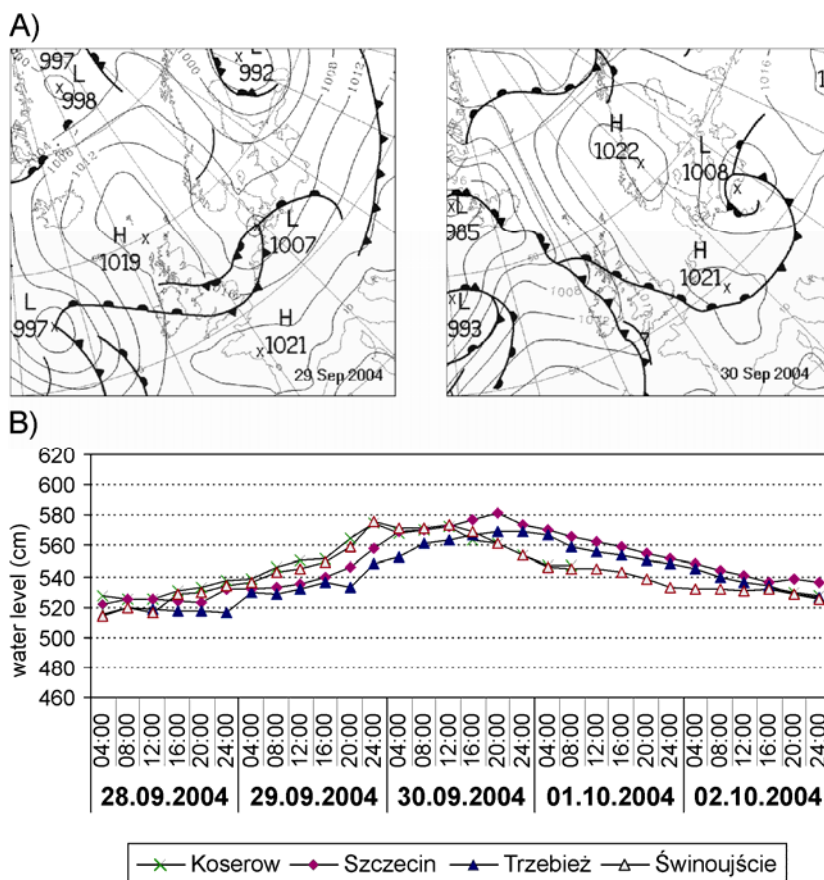


Fig. 4. The synoptic situation: A – after <http://www.wetterzentrale.de/topkarten/fsfaxsem.html> and water levels in the Odra River mouth area; B – during the 28 September–2 October 2004 storm surge.

During this storm surge, the Szczecin Lagoon water level fluctuations followed, with a time lag, the sea level changes (Fig.4B). On 29 September, under the prevailing north-westerly winds, the water level began to rise and first exceeded the warning level and then the alarm level. The maximum water levels were observed 20 h after the sea level maximum in Świnoujście. In Trzebież, a maximum of 569 cm was recorded on 30 September at 8 p.m.; the maximum in Ueckermünde was 577 cm, and was recorded at 10 p.m. heightened water levels also were observed in the downstream Odra reach. In Szczecin, a maximum of 581 cm occurred on 30 September at 8 p.m. In Gryfino that day the water level rose to 572 cm, and in Widuchowa the water level increased by half a metre. The slight eastward shift of the low caused the water level within this region to drop.

A wind- and baric wave-caused storm surge, with a typical wind-driven backflow (22–25 November 2004)

The storm surge observed on 22–25 November 2004 was caused by the passage of a deep low-pressure system moving from the North Sea over the central part of the Baltic Sea and finally eastwards (Fig.5A). Initially, on 22 November, the water level along the Pomeranian Bay coast dropped rapidly as a result of the passage of the low (991 hPa in the centre) over the North Sea and the development of a high-pressure system over Central Europe. This situation resulted in the outflow of Baltic water into the North Sea and additionally generated a system of S–SW winds along the Pomeranian coast. In Koserow and Świnoujście, the sea level dropped to 480 and 473 cm at noon, respectively (Fig.5B). The sea level then began to rise rapidly to reach a maximum on 23 November as a result of the low centre's rapid shift over the central Baltic (984 hPa in the centre) and northerly winds. In Koserow, a maximum of 637 cm was recorded at 9 p.m.; the maximum in Świnoujście was 629 cm, and was recorded at 8 p.m. Subsequently, the low shifted eastwards and the high over Central Europe developed, generating south-westerly winds at the Pomeranian coast that resulted in a significant decrease in the water level at the Pomeranian coast during the next few days (negative phase of the baric wave). The minimum sea level was observed on 25 November. In Świnoujście and Koserow, the minimum was 466 cm (noon) and 448 cm (10 a.m.), respectively.

During this storm, the water level of the Szczecin Lagoon changed with a time lag relative to the changes in the sea level. From 22 to 24 November, the Lagoon water level was observed to continuously increase (by half a metre) (Fig.5B). The Trzebież maximum level of 570 cm was recorded at noon, the Ueckermünde maximum level of 579 cm occurred at 11 a.m.; thus, the time lag

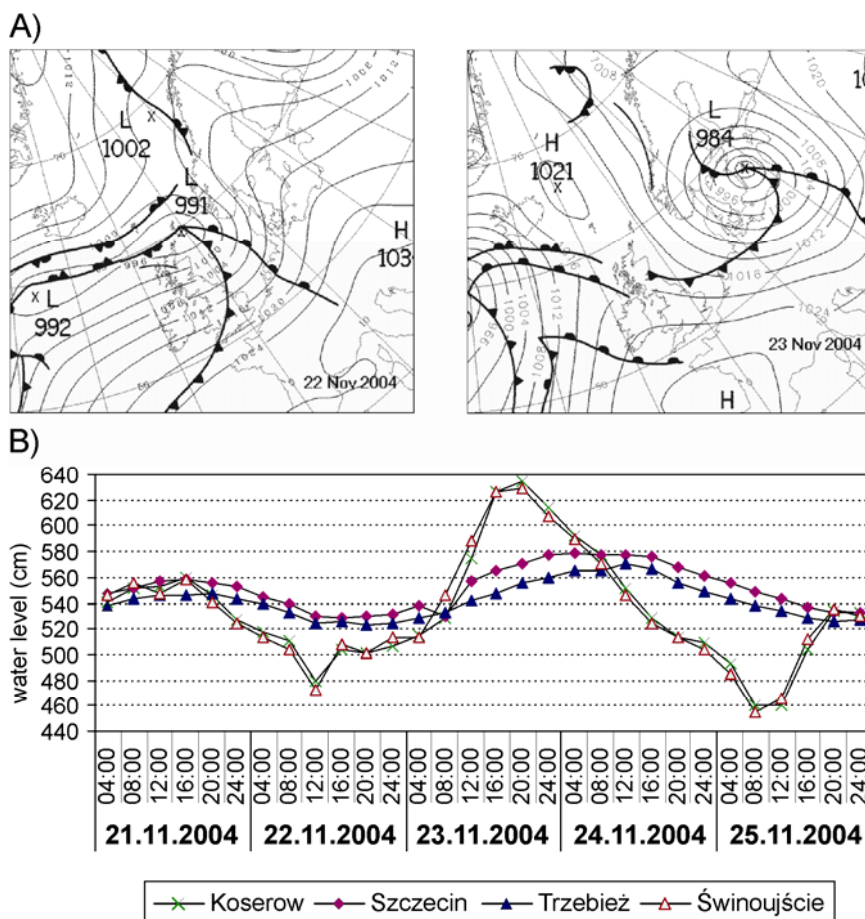


Fig. 5. The synoptic situation: A – after <http://www.wetterzentrale.de/topkarten/fsfaxsem.html> and water levels in the Odra river mouth area; B – during the 21-25 November 2004 storm surge.

was 16 and 15 hours, respectively, relative to the sea level maximum. Over the subsequent days, the water level was observed to drop slowly.

During the storm surge, an increase in the water level was observed in the Lower Odra channels from 22 November. In Szczecin, the water level maximum of 579 cm was recorded at 4 a.m. on 24 November. In Gryfino, the water level maximum of 583 (a 44 cm increase) was observed on 24 November as well. In Widuchowa and Gozdowice, increases of 42 cm and 29 cm, respectively, were recorded. Subsequently, the water level was observed to drop slowly in the downstream Odra reach.

A wind- and baric wave-caused storm fall (17-22 December 2004)

A deep storm fall on 22 December 2004 at the Pomeranian coast was the result of the passage of a low-pressure system, with 988 hPa at the centre, from the Alps over the central Baltic and then over the White Sea. Initially, from 17 December, the water level at the Pomeranian coast was observed to increase. On 19 December, the sea level reached a maximum (565 cm in Świnoujście at 8 p.m.), resulting from the relocation of the low over the central part of the Baltic Sea and strong (6°B) NNW winds (Fig.6A). During the next two days, the low moved towards the White Sea and a high with 1031 hPa at the centre developed

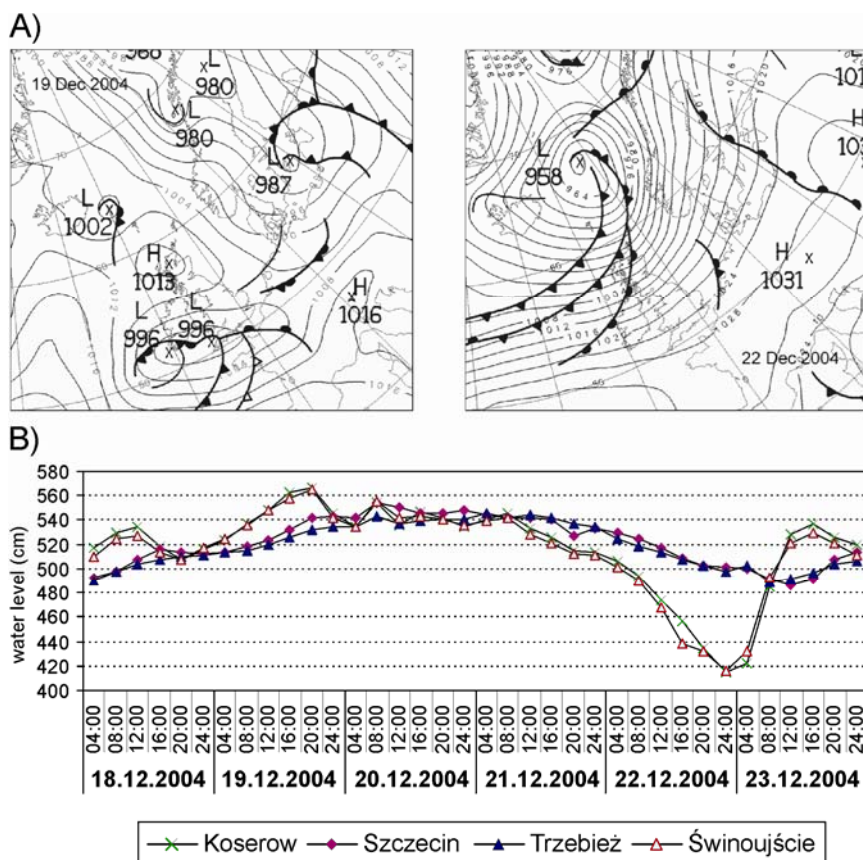


Fig. 6. The synoptic situation: A – after <http://www.wetterzentrale.de/topkarten/fsfaxsem.html> and water levels in the Odra River mouth area; B – during the 17-22 December 2004 storm surge and fall.

over Central Europe, generating the system of SW, and then SSW, winds that resulted in a rapid drop of the sea level at the Pomeranian coast. The lowest sea level was observed during the night of 22 December. In Świnoujście, a level of 416 cm was recorded (Fig. 6B), with 415 cm being recorded in Koserow. This minimum was the result of an overlap of the negative phase of the baric wave and winds pushing the water offshore. Subsequently, sea level was observed to increase.

During this storm surge, water level fluctuations in Szczecin Lagoon and in the Lower Odra channels were significantly weaker and occurred with a time lag relative to sea level changes. The Trzebież maximum water level of 546 cm was observed on 21 December at 4 a.m. (Fig. 6B). In the downstream Odra reach, the water level did not exceed warning levels. During the night of 22 December, only a slight drop in the water level was observed. The level dropped to 489 cm on 23 December at 8 a.m. in Trzebież and to 486 cm at noon in Szczecin, mainly as a result of southerly winds. The water level drops in Gryfino and Widuchowa were negligible.

CONCLUSIONS

Passages of deep low-pressure systems over the Baltic Sea cause storm surges and storm falls in the Odra river mouth area. The effects of wind action and changes in atmospheric pressure at the sea surface can be additive, in which both factors increase or decrease the sea level at the coast. They can be also non-additive, with one factor increasing the sea level while the other decreases it. The cases examined showed varying impacts of both factors.

The study revealed the following typical scenarios:

1. Wind- and baric wave-caused storm surges with a typical wind-driven backflow in the Odra branches. In such cases, the water level was observed to increase, first at the Pomeranian Bay coast, then in the Szczecin Lagoon, and finally in the Lower Odra channels. The maximum level resulted from an overlap of the positive phase of the baric wave with winds from the northern sector. Subsequently, the water level was observed to drop as a result of the movement of the low outside the Baltic, coupled with an increase in air pressure. The effect of the negative phase of the baric wave on the sea surface was very distinct. In the Szczecin Lagoon and along the downstream Odra reach, water level fluctuations were weaker and followed, with a time lag, the changes in sea level.

2. Storm surges with a typical wind-driven backflow in the Odra branches and high water levels in the Lower Odra channels and the Szczecin Lagoon. Under these circumstances, the rise in water levels caused by the passage of a deep low-pressure system over the Baltic Sea was stronger, occasionally

resulting in flooding events. Such situations were common in spring, as a result of ice thaw and accumulation of water from a previous storm surge.

3. Short-lived storm surges, registered only at the Pomeranian Bay coasts. The surges were generated by a rapid shift of a deep low over the Baltic Sea and by appropriate winds. The effect of the low's movement was often negligible in the Szczecin Lagoon and the downstream Odra reach because the hydrodynamic capacity of the straits connecting the Lagoon with Pomeranian Bay was too low.

4. Storm surges caused primarily by strong wind. In such surges, both the increasing and decreasing phase of changes in the water level were slow and mild. The pressure effect was imperceptible. Heightened water levels were observed in the Pomeranian Bay and the Szczecin Lagoon as well as along the downstream reach of the Odra.

5. Storm falls. Deep storm falls (below 440 cm NN) were recorded during passages of deep low-pressure systems as a result of the negative phase of the baric wave and southerly winds. They were particularly deep when a high-pressure system over the Baltic Sea developed and a low was passing over the North Sea. Such cases were additionally accompanied by an outflow of Baltic water into the North Sea.

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