Physical aspects of extreme storm surges and falls on the Polish coast

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Bernard Wiśniewski[1]
Tomasz Wolski[2,⋆]

[1] Faculty of Navigation,
Maritime University of Szczecin,
Wały Chrobrego 1–2, Szczecin 70–500, Poland

[2] Faculty of Geosciences,
University of Szczecin,
al. Wojska Polskiego 107/109, Szczecin 70–483, Poland;

e-mail: natal@univ.szczecin.pl

⋆corresponding author

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Abstract

Extreme sea levels – storm-generated surges and falls – on the Polish coast are usually the effects of three components: the volume of water in the southern Baltic (the initial level preceding a given extreme situation), the action of tangential wind stresses in the area (wind directions: whether shore- or seaward; wind velocities; and wind action duration), and the sea surface deformation produced by deep, mesoscale baric lows moving rapidly over the southern and central Baltic that generate the so-called baric wave. Among these factors, the baric wave is particularly important for, i.e. the water cushion underneath the baric depression, moving along the actual atmospheric pressure system over the sea surface.

1. Introduction

The sea level in the Baltic changes considerably throughout the year as a result of the superimposing effects of a number of meteorological and hydrographic factors. The relevant literature emphasizes the contribution

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

of the wind field to sea level variations, particularly during storm situations. In addition, various authors list other factors which produce, or contribute to, sea level changes: water exchange between the Baltic and the North Sea, riverine discharges into the Baltic, seasonal changes in water density, atmospheric precipitation and evaporation, and seiches (Heyenet al. 1996, Samuelsson & Stigebrandt 1996, Carlsson 1998). On the other hand, tidal effects are irrelevant for sea level changes in the Baltic (Suurssar et al. 2003, 2006, Jasińska & Massel 2007).

A particular type of sea level change is a storm surge. Storm surges and falls are defined as short-term, extreme variations in the sea level. Short-term variations are changes of the sea level recorded within several minutes to a few days. They include sea level oscillations intermediate between wind-generated waves and seasonal sea level changes. The coastal protection services describe a storm surge as a dynamic rise of the sea level above the alarm or warning level, induced by the action of wind and atmospheric pressure on the sea surface.

Storm surges have always been of interest to chroniclers and scientists. Therefore, their descriptions, both historical and recent, are numerous. The history of the Baltic Sea and old chronicles of major Pomeranian towns are a treasure trove of information on the type and effects of disastrous surges. The maximum sea levels during storm surges that caused heavy flooding used to be denoted by the high-water marks painted on old buildings or other objects. The most distinct evidence of storms and disastrous wave activity is visible in the church at Trzęsacz. When built in 1250, the church stood in the middle of the village, 700 m away from the Baltic shore. By 1868, the church found itself on the edge of a cliff, and after 1900 it gradually began to disappear into the sea. What remains today is a single wall, protected from further destruction by heavy seas. Of all the Polish coastal stations, Kołobrzeg was the site of the absolutely highest sea level (2.22 m above the Normal Null, N.N.), recorded on 13 November 1872. That storm surge was observed in numerous ports of the western Baltic coast where the water rose by as much as 3 m above the mean level. Storms and the associated surges have been described and analysed in numerous publications; the most comprehensive descriptions in the Polish literature are those of Majewski et al. (1983), Majewski (1986, 1989, 1997, 1998a,b), Sztobryn et al. (2005, 2009) and Wiśniewski & Wolski (2009). These publications and annual records have served as a basis for a summary of historical data on extreme sea levels along the Polish coast (Table 1).

Nineteenth-century and earlier descriptions of floods are mainly of historical importance. The coastal conditions at those times were different from the present-day hydrography of the area, as the morphology of river

Table 1. Extreme sea levels [cm] along the Polish coast (tide gauge zero = 500 cm N.N.)

Tide-gauge	Maximum sea level [cm]	Date of occurrence	Minimum sea level [cm]	Date of occurrence
Świnoujście	696	10 Feb. 1874	366	18 Oct. 1967
Dziwnów	615	10 Feb. 1874	410	4 Feb. 1960
Kołobrzeg	722	13 Nov. 1872	370	4 Nov. 1979
Darłowo	659	9 Jan. 1914	393	10 Feb. 1897
Ustka	668	15 Dec. 1898	396	10 Feb. 1897
Łeba	668	15 Dec. 1898	403	31 Dec. 1890
Władysławowo	644	23 Nov. 2004	412	4 Nov. 1979
Hel	622	14 Jan. 1993	405	Jan. 1904
Gdynia	632	23 Nov. 2004	414	Feb. 1937
Gdańsk	664	16 Dec. 1843	395	20 Jan. 1887
Świbno	702	5 Dec. 1899	413	10 Feb. 1897

mouths and harbour areas as well as harbour infrastructures have changed significantly since. However, some descriptions imply that surges were caused not only by storms, but could also have been elicited by swell waves appearing on the sea surface as a result of an earthquake or a large meteorite fall. However, the determination of cause-effect relationships and relevant correlations is precluded for lack of numerical data and timing records. The study of the characteristics of extreme storm surges and falls involves practical aspects and allows to determine, among other things, warning and alarm levels, which are of importance for, e.g. flood and coastal protection services as well as those involved in the safety of shipping.

This aim of this study was to explain the physical aspects of storm surges and falls in the sea level along the Polish coast, and to indicate the value of these aspects for the modelling and forecasting of storm surges.

2. Material and methods

The analysis was performed for three characteristic storm surge events differing in the effects of the baric factor on the maximum sea level rise or fall. The events selected occurred on 16–18 January 1955, 17–19 October 1967 and 13–14 January 1993. In this work we calculated the values of the static and dynamic deformation of the sea surface as the result of the passage of a baric low. For this purpose we used the following formulae (Lisowski 1961, Wiśniewski 1983, 1996, 1997, 2005, Wiśniewski & Wolski 2009):

$$\Delta H_s = \frac{\Delta p}{\rho \times g}, \tag{1}$$

where

ΔH_s [cm] – static increase in sea level at the centre of the low pressure area,

Δp [hPa] – rise or fall in atmospheric pressure in relation to its average value, i.e. 1013.2,

ρ – mean water density – 1.010 g cm^{-3},

g – acceleration due to gravity – 981 cm s^{-2};

and

$$\Delta H_d = \frac{\Delta H_s}{1 - \left(V_L/\sqrt{g \times H_m}\right)}, \tag{2}$$

where

ΔH_d [cm] – dynamic deformation of sea level,

V_L [m s^{-1}] – travelling velocity of the air pressure system,

H_m [m] – average sea depth in the outer port.

The calculations were performed for five ports (tide-gauge stations) on the Polish coast: Świnoujście, Kołobrzeg, Ustka, Władysławowo and Gdańsk. In addition, the following characteristics were determined for each storm surge:

- (p_i) – the pressure at the centre of the depression [hPa],
- the initial sea level [cm] (the sea level prior to the occurrence of an extreme event),
- extreme values of the sea level during the surge and their amplitude [cm],
- rates of the maximum sea level rise and fall [cm h^{-1}].

Sea level changes during each storm surge event were illustrated by graphs, and synoptic maps showing the passage of the low pressure systems involved were developed. In addition, the baric situation during each event was described, with reference to the course of the storm surge along the Polish coast.

Data on the water level series and weather conditions were obtained from *Hydrographic year-book for the Baltic Sea (1946–1960)*, *The maritime hydrographic and meteorological bulletin (1961–1990)*, *The environmental conditions in the Polish zone of the southern Baltic Sea (1991–2001)*, the archives of the Institute of Meteorology and Water Management (IMGW 2009) and the Maritime Institute, as well as the logs kept by harbour masters.

3. Results

Table 2 contains data describing the features of the baric lows, observed sea levels, as well as static and dynamic deformations of the sea surface, calculated using formulae (1) and (2), in the vicinity of the ports listed above. The static surge is reliable for the southern Baltic for a stationary baric low centre. The dynamic sea surface deformation ought to characterize the actual effect of the low on the sea level in the vicinity of the coast, but it does not involve the so-called shallow water factors such as friction, energy dissipation rate in the outer port and the roads. The mathematical expression of such factors has to be yet developed for storm situations. The world literature contains shallow-water factors for tides, i.e. regular, periodic sea level changes.

3.1. The storm of 16–18 January 1955

A very active low pressure system which advected over the southern Baltic produced a rapid sea level rise. This system passed from the south of England via the North Sea coast to the southern Baltic coast, from where it moved on to the Gulf of Finland (Figure 1a). The high horizontal pressure gradient component in the western part of the system was accompanied by a strong, gusty, north-westerly wind. The entire Polish coast experienced a rapid sea level rise (maximum of 617 cm, i.e. 117 above zero N.N., at Świnoujście on the western part of the coast, 635 cm at Kołobrzeg, and 615 cm at Gdańsk on the eastern part of the coast) (Figures 1b, c). The low was moving from over the Pomeranian Bay towards the eastern part of the coast with a mean velocity of 50 km h^{-1} and passed over the Polish coast in the space of 6 hours. The low pressure system's velocity affected not only the magnitude of the sea level rise, but also its intensity. All the gauges showed only the positive phase of the sea surface deformation. On 17 January 1955, the wind at Świnoujście changed direction from S to SW and NW, and could not, by itself, have generated the surge. The contribution of the baric wave to the surge is obvious and visible in Figures 1a–1c and in Figure 2, which shows a rise in sea level of 90 cm during 2 hours and a fall of 90 cm during 4 hours.

3.2. The storm of 17–19 October 1967

A deep and active low pressure system from over the British Isles was moving at a velocity of 70 km h^{-1} over Denmark and southern Sweden, the Baltic Sea and on towards the north-east into the White Sea (Figure 3). The storm wind and baric wave generated by the system induced extremely large variations in the Baltic sea level. The rapid passage of the low over

Table 2. Parameters of the storm surges and falls analysed

The storm date	Port	H_m	Attribute of depression		Observed sea level						ΔH_s	ΔH_d
			p_i	V_L	Initial sea level	Max	Min	Amplitude	Maximum sea level rise rate	Maximum sea level fall rate		
		[m]	[hPa]	[m s^{-1}]	[cm]	[cm]	[cm]	[cm]	[cm hour^{-1}]	[cm hour^{-1}]	[cm]	[cm]
16–18	Świn.	30			497	617	482	135	45	35		255
Jan.	Kołob.	40			499	635	494	141	50	25		163
1955	Ustka	40	965	13.9	495	620	492	128	55	40	48.6	163
	Wład.	45			501	604	495	109	25	20		144
	Gdańsk	50			500	615	492	123	46	38		130
17–19	Świn.	30			484	586	366	220	46	56		–
Oct.	Kołob.	40			510	599	414	185	56	50		–
1967	Ustka	40	970	19.4	509	594	437	151	40	52	43.6	–
	Wład.	45			519	583	475	108	20	30		–
	Gdańsk	50			522	604	466	138	42	46		–
13–14	Świn.	30			476	540	392	148	72	40		−48
Jan.	Kołob.	40			490	560	437	123	70	46		−68
1993	Ustka	40	972	31.9	498	590	452	130	40	90	41.6	−68
	Wład.	45			500	596	484	112	58	40		−80
	Gdańsk	50			497	624	470	154	48	78		−94

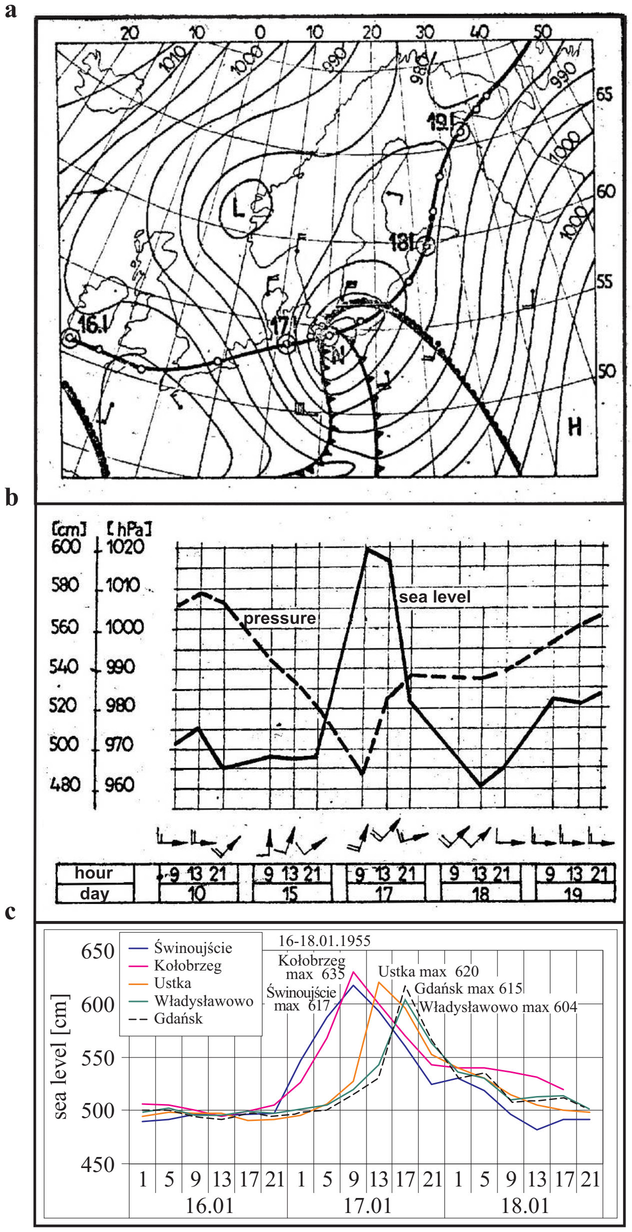

Figure 1. The storm surge event along the Polish coast 16–18 January 1955 caused by a baric wave. Synoptic chart (a), sea level and pressure at Świnoujście (b), sea level changes in the Polish ports studied (c)

the Baltic resulted in a characteristic sea level fall on the Polish coast on the morning of 18 October. At Świnoujście, the absolute 1946–2006 minimum

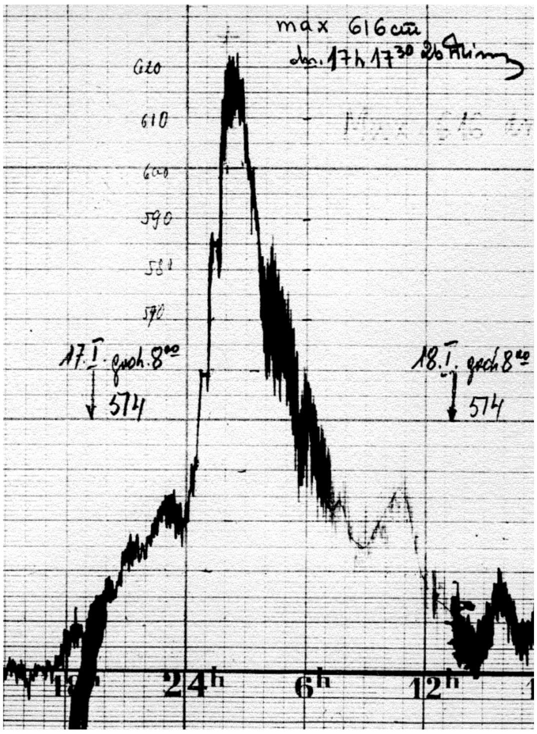

Figure 2. A tide gauge record of the sea level changes at Gdańsk (17 January 1955); (IMGW 2009)

of 366 cm was recorded. The low's centre moved that day over the Åland Archipelago. For some hours the southern Baltic, left in the rear of the baric system, experienced severe north-westerly and northerly winds. The return to equilibrium proceeded through wind-induced seiche-like changes in the sea level. At Świnoujście and Kołobrzeg, the sea level changes during 8 h had an amplitude of about 2 m (Figure 4). It should be pointed out that, when the baric low movement is close to the value of $\sqrt{gH}$, as was the case in the event of 17–19 October 1967, the denominator of formula (2) tends to 0. In this case, formula (2) suggests that the storm situation should be covered by the resonance zone, and the result of the calculations is not reliable. On the other hand, the maximum rises and falls of the sea level, as shown by the mareograms of 17–19 October 1967, did not indicate the differences relative to the remaining surges and falls analysed.

3.3. The storm of 13–14 January 1993

On 14 January, an active low pressure system, the so-called 'junior', passed – along with atmospheric fronts – from over the North Sea via the

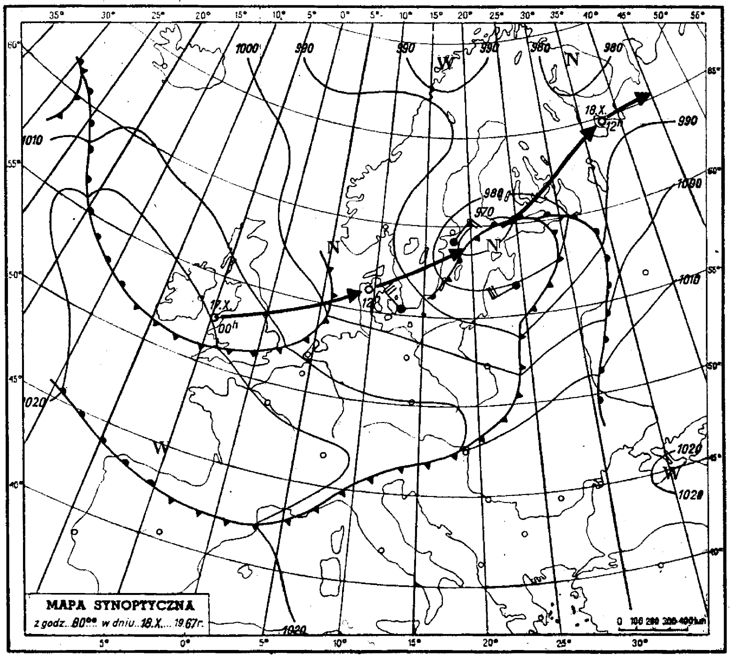

Figure 3. Synoptic chart of the 18 October 1967 event (Majewski et al. 1983)

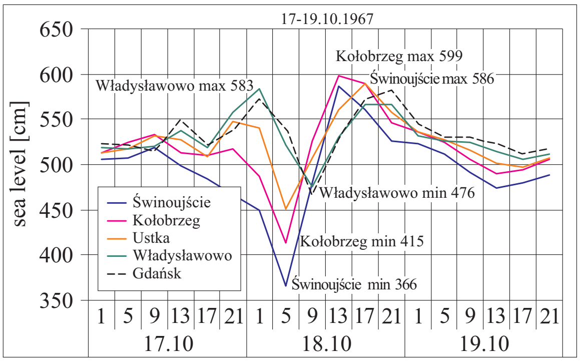

Figure 4. Example of the storm surge and fall on 17–19 October 1967 caused by the pressure-induced wave

Danish Straits into the Baltic (Figures 5 and 7a). The atmospheric low was as deep as 972 hPa. Typical of the sea level changes during that storm was the large amplitude of variations in the eastern and western parts of the coast. Figures 6 and 7b show the sea level rises and falls, moving eastwards in parallel with the low centre passage (the movement of the wave crest from 04:00 to 08:00 hrs UTC on 14 January 1993). The storm

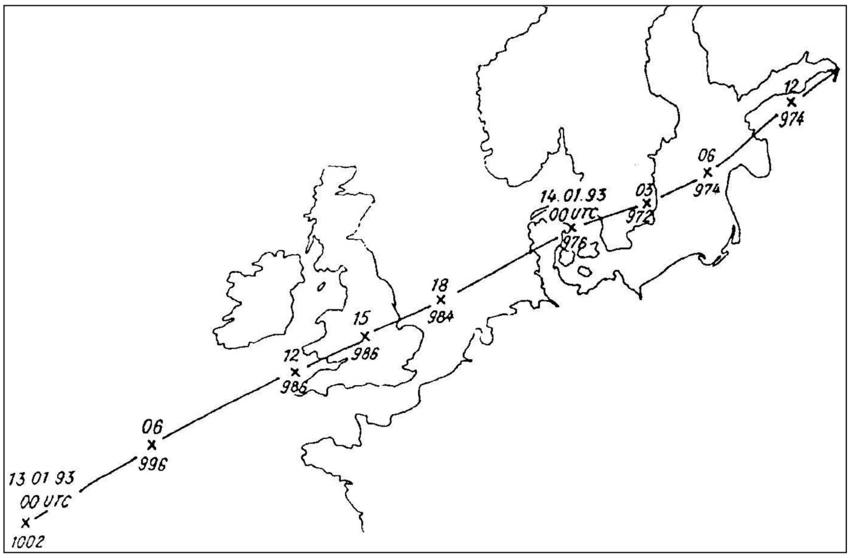

Figure 5. The route of centre of the storm low-pressure system for the period from 13 January, 00 UTC to 14 January, 12 UTC, 1993 (Wiśniewski 1997)

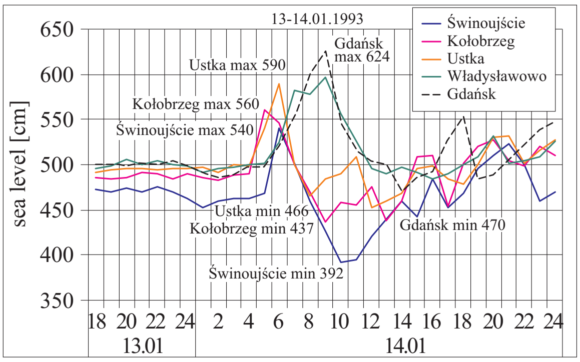

Figure 6. Changes in sea level along the Polish Baltic coast from 18:00 hrs on 13 January to 24:00 hrs on 14 January 1993

surge involved a sea level deformation by the baric wave with its positive and negative phase. Significant here was the high velocity (about 115 km h^{-1}) of the low's passage, which greatly affected the wave's dynamic component involving a ratio between the passage velocity and the depth of the area ($V_L \gg \sqrt{gH_m}$). Considering the inaccuracy with which formula (2) models the actual situation, the involvement of the wind field in the sea surface deformation in the low is visible on the mareograms of 14 January 1993. An important feature of the storm surge in question was the very rapid rise

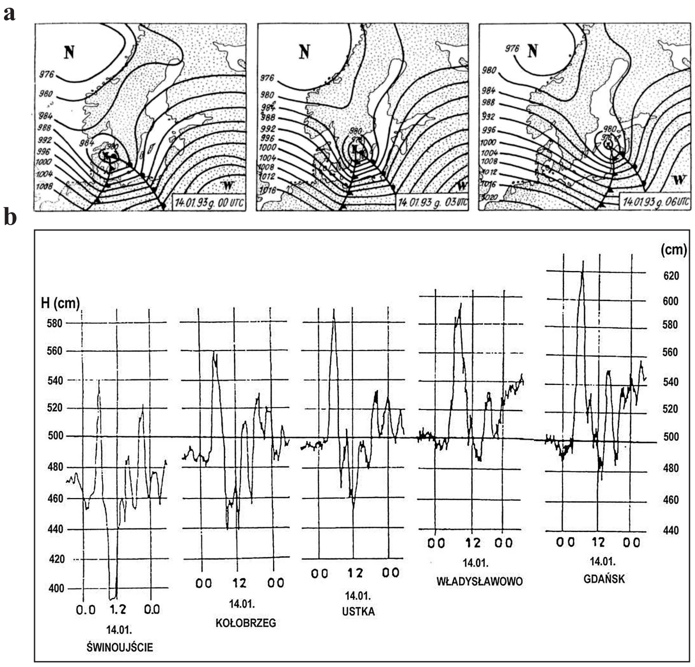

Figure 7. Synoptic chart (a). A mareographic record of sea level changes in Polish ports (b); (IMGW 2009)

and fall of the sea level (Table 2), which is of significant practical importance for forecasting the under-keel clearance when a ship enters or leaves a port. The storm lasted for scarcely 5 hours, but in that time caused severe damage on the coast and triggered the *Jan Heweliusz* ferry disaster at sea.

4. Discussion

As a rule, the occurrence of extreme sea levels – storm surges on the Polish coast, is dependent on 3 components:

- the volume of water in the southern Baltic (the initial sea level prior to the occurrence of an extreme event),
- the action of tangential wind stresses in an area (wind directions: whether shore- or seaward; wind velocities; and wind action duration),
- deformation of the sea surface by the mesoscale baric lows passing rapidly over the southern and central Baltic, which produces the so-called baric waves and generates seiche-like variations of the sea level in the Baltic.

The volume of water filling an area prior to the extreme sea level has been mentioned in a few publications in the Polish sea coast context (storms in the southern Baltic) (Wiśniewski 1996, Stanisławczyk & Sztobryn 2000, Sztobryn et al. 2005, Wiśniewski & Wolski 2009). For example, the volume of water filling a basin was determined by calculating, from observational data, a mean sea level along the Kołobrzeg–Kungsholmsfort transect or by reference to records from other ports, e.g. Degerby or other transects in the Baltic (Stanisławczyk & Sztobryn 2000). A general account of water exchange between the North Sea and the Baltic and changes in the Baltic water volume produced by long-lasting stationary baric systems was published by Wielbińska (1962). An example of a true water volume in the southern Baltic is furnished by the sea level records at Świnoujście in January 2007 (Figure 8). A sequence of fast-moving low pressure systems passing from the Atlantic to the Baltic resulted in a large inflow of the North Sea water into the Baltic. The linear trend showed the averaged sea level at Świnoujście to have changed from 511 to 570 cm N.N. Under such conditions, the level of 570 cm N.N. was exceeded several times in the second half of January.

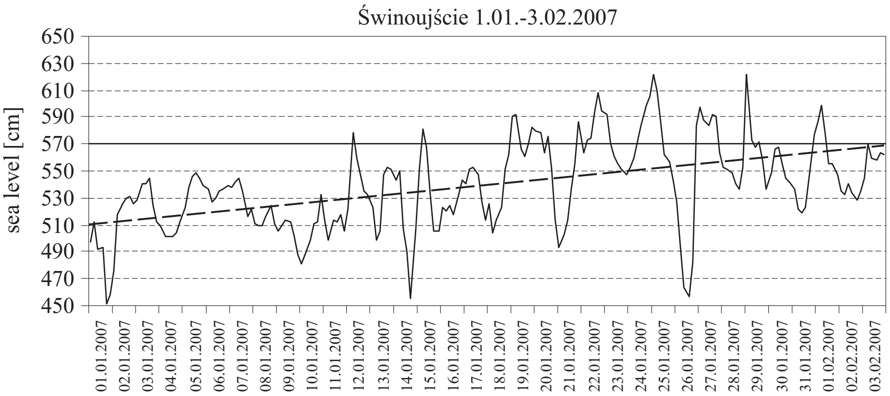

Figure 8. Sea level changes at Świnoujście in January 2007 (Wiśniewski & Wolski 2009)

In the three storm situations analysed in this work, the basin filling is represented by the starting (reference) sea level prior to the occurrence of the storm-caused changes (Table 2). In all three situations, the level was similar to the mean sea level (500 cm N.N.), except for the level of 476 cm at Świnoujście on 13 January 1993.

The role of tangential wind stresses in the emergence of drift currents and their resultant contribution to the rise or fall of sea level in the ports of an area is understandable; the magnitude of a rise or fall depends not only on the wind speed, but also on the wind duration, direction, wind fetch over the sea surface, and compensatory flows in the inshore zone. The wind effects are directly related to the pressure distribution over an area. If water molecules move onshore, the presence of land will contribute to the kinetic energy of the flow being transformed into forces raising those molecules up to a 'higher level', i.e. the emergence of a surge in the inshore zone. If the wind blows seawards, the sea level in the inshore zone will fall. However, as shown by tide gauge records, true sea level surges and falls can be several times higher than the values resulting from the action of tangential wind stress upon the fluid surface (Wiśniewski & Holec 1983). Suursaar et al. (2003) pointed out that the highest surge events on the west Estonian coast are associated with deep cyclones producing strong SW and W winds in suitably oriented bays such as Pärnu Bay. As reported by Suursaar et al. (2006), cyclone Gudrun, which occurred in January 2005, caused the heaviest storm surge along the coasts of the Gulf of Riga. The sea level at Pärnu was 2.75 m higher than the mean level there. In the Gulf of Finland, new records of sea level increase were measured as well, e.g. in Helsinki (1.51 m). Skriptunov & Gorelits (2001) showed that significant wind-induced variations in the water level near the River Neva as well as their magnitude and duration result from the wind regime and the morphology of the near-mouth offshore zone. Averkiev & Klevanny (2007) analysed the effects of atmospheric pressure as well as wind direction and speed on the sea level in the Gulf of Finland. They showed the cyclone trajectory to be potentially important in generating storm surges particularly damaging for St. Petersburg (Russia).

The problem of sea level deformation by concentric, mesoscale, fast-moving deep baric lows was tackled by Lisowski (1960, 1961, 1963), Wiśniewski & Holec (1983) Wiśniewski (1996, 1997, 2003, 2005), Wiśniewski & Kowalewska-Kalkowska (2001, 2003, 2007), Wiśniewski & Wolski (2009). It seems, however, that this factor has been generally underestimated, even downright ignored, in the literature, a situation that has been detrimental to attempts at explaining mechanisms of such extreme phenomena as coastal floods or low sea levels that adversely affect navigation safety, hydrotechnical construction stability, etc.

To be sure, a lowered atmospheric pressure system (a tropical cyclone or a concentric baric low) overlies a water cushion, the so-called baric wave, moving together with the pressure system at the sea surface. The wave's height depends on the pressure decrease in the centre of the system. A pressure drop of $\Delta p = 1$ hPa results in a static sea level rise of $\Delta H_s = 1$ cm at the stationary low (Figure 9a, Formula 1). When the low moves over the sea surface, the latter becomes dynamically deformed (ΔH_d). The sea level deformation associated with the baric wave shows positive wave elevations in the centre and negative elevations on the flanks of the deformation

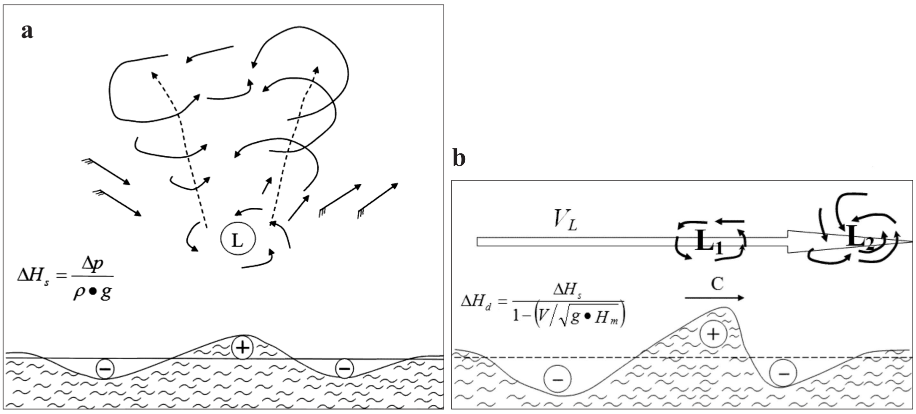

Figure 9. Diagram of sea surface deformation caused by a low pressure system static sea surface deformation (a), dynamic sea surface deformation (b) (Wiśniewski & Wolski 2009)

(Figure 9b, Formula 2). During the passage of a deep low, the sea level rise may be 2–4 times higher than the rise produced by static conditions. The fluid level deformation moves according to the laws of forced long wave propagation. When the wave propagation velocity is close to that of a baric system passage, the wave amplitude will reach large values under the dynamic parameters of the system.

As a result of the progressive movement of a baric low, the ratio of low progression (VL) to the free wave characteristics becomes important:

$$c = \sqrt{gH_m}, \tag{3}$$

where

H_m – average sea depth,

g – acceleration due to gravity – 981 cm s^{-2}.

Besides, an additional disturbance taking the form of diverging transverse waves is propagated perpendicularly to the passage trajectory of the baric system. The waves look like those generated by a ship's movement. The amplitude of these additional disturbances should be expected to be lower than that of the basic sea level deformation caused by the baric wave. In addition to the major forced wave, i.e. the wave propagating at the speed of the baric system, there can be additional free long waves associated with the rapid change in the baric low velocity or direction.

Thus, storm-generated surges and falls of sea level are a net effect of wind action and a baric wave resulting from the baric field characteristics. Wind and a baric wave can produce the same effect, i.e. both factors cause the sea level on the coast to rise or fall; they can also produce opposite effects, when one factor raises the sea level and the other lowers it. The effects of a baric wave may be several times greater than those of the wind action. When the storm (baric wave, wind) abates, the sea level – knocked out of balance – will undergo free damped oscillations until equilibrium is restored (seiche-like variations).

Owing to the complexity of the phenomenon, any sea level forecast during a storm surge will be problematic. An additional difficulty is that sea level changes are greatly affected by local conditions on the coast and the seafloor relief in the inshore zone and in a port. Therefore, it is necessary that the sea surface deformation factor by the rapidly moving baric low be included in future models developed to forecast storm surges and falls.

The contribution of sea surface deformation by rapidly moving, deep, mesoscale baric lows to the overall picture of sea level rises and falls is confirmed by the examples of storm events selected for this work, i.e. 16–18 January 1955, 17–19 October 1967 and 13–14 January 1993 (Figures 1–7).

5. Conclusions

The interactions between wind and baric waves during storm surges allow one to observe that:

- the relative contributions of wind and baric wave to the resultant changes in sea level depend on mesoscale baric lows, their passage velocity and intensity. Deep (< 980 hPa), rapidly moving baric lows cause sea surface deformation mainly as a result of baric wave action. When a baric low system moves at high speed, the wind action in a given direction is limited in duration. The wind energy produces waves and mixes the water, but cannot induce pronounced drifting surges. On the other hand, when baric systems are shallow (> 980 hPa) and slow-moving, the resultant change in the sea level is brought about predominantly by the wind field;
- the type of sea level change (amplitude and timing) is greatly affected by the baric low's trajectory and its distance from the shore. A large positive wave effect occurs when the trajectory is parallel to the coast – in such a case, local conditions play an important part;
- exceptionally severe storm surges occur when the baric wave crest (positive phase) approaching the Polish coast is in harmony with the on-shore direction of the wind.

The sea surface deformation factor by the rapidly moving baric low should be included in future models developed to forecast storm surges and falls.

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