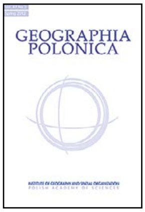


Geographia Polonica
2026, Volume 99, Issue 2, pp. 147-165
https://doi.org/10.7163/GPol.0321

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
www.igipz.pan.pl

www.geographiapolonica.pl

SEA-LEVEL TRENDS ALONG THE POLISH COAST IN THE CONTEXT OF CHANGES IN THE GLOBAL OCEAN AND THE BALTIC SEA

Tomasz Wolski

Institute of Marine and Environmental Sciences
University of Szczecin
Mickiewicza 18, 70-383 Szczecin: Poland
e-mail: tomasz.wolski@usz.edu.pl

Abstract

Sea level changes are among the key manifestations of contemporary climate change. This review article presents the current state of knowledge regarding global and regional drivers of sea-level variability, with particular emphasis on the specific characteristics of the semi-enclosed Baltic Sea basin and the role of post-glacial isostatic adjustment (GIA) processes. A review of available studies indicates that the Polish coast is characterized by an increasing trend in relative mean sea levels (RSL), which have been rising at a rate of 2 mm·yr^{-1} since the mid-20th century – averaging 15 cm over the last 75 years. The main causes of these changes are global factors (global mean sea-level rise – GMSL) and, to a lesser extent, coastal subsidence processes. Satellite and tide gauge data in the 21st century indicate significant acceleration in both relative (RSL) and absolute sea level (ASL) rise along European and southern Baltic coasts, directly resulting from anthropogenic climate change. Projections of further sea-level rise are deeply alarming for Polish administration. According to the Intergovernmental Panel on Climate Change (IPCC), depending on greenhouse gas emission scenarios, the rate of RSL rise may reach 6-7 mm·yr^{-1}– more than three times higher than from the mid-20th century to present -which further increases the risk of erosion and storm flooding for the Polish coast.

Keywords

sea-level trends • Baltic Sea • global ocean • Polish coast • relative sea-level change (RSL) • absolute sea-level change (ASL)

Introduction

Sea-level rise is among the best-documented and most consistent manifestations of contemporary climate change. Instrumental observations, including long-term tide-gauge records as well as satellite altimetry data available since the early 1990s, unequivocally indicate a positive trend in global mean sea level (GMSL), the rate of which has accelerated in recent decades. According to the latest assessment reports of the Intergovernmental

Panel on Climate Change (IPCC), the rise in global ocean level results from processes operating at the planetary scale, primarily ocean thermal expansion and the ongoing mass loss of mountain glaciers and the Greenland and Antarctic ice sheets (IPCC, 2022; IPCC AR6, 2023). These changes represent a long-term trend whose impacts will continue to unfold throughout the twenty-first century.

At the same time, sea-level change is not spatially uniform. Regional and local departures from the global trend arise from the influence of additional factors, including variability in oceanic and atmospheric circulation, regional differences in ocean heat content, redistribution of mass within the Earth–ocean–lithosphere system, and vertical crustal movements. As a consequence, relative sea-level change (RSL) observed along individual coastlines may differ substantially in magnitude, direction of trend, and dominant temporal scale of variability (Pugh, 2004; Church et al., 2013).

The Baltic Sea constitutes a distinctive example of a coastal basin in which observed sea-level variability results from a complex interplay of global, regional, and local processes. As a shallow, semi-enclosed shelf sea connected to the North Sea through narrow and shallow straits, the Baltic Sea is characterized by limited water exchange and high sensitivity to atmospheric forcing. Water-level fluctuations in this basin occur over a broad range of temporal scales – from short-term variations driven by wind forcing and atmospheric pressure changes, through seasonal and interannual variability, to long-term trends associated with global ocean rise and vertical land motion (VLM) (BACC II Author Team, 2015; Hünicke et al., 2015; Meier et al., 2022a; Rutgersson et al., 2022).

Isostatic processes constitute a key factor shaping sea-level change within the Baltic Sea basin. In the northern part of the region, positive vertical crustal movements dominate, leading to a relative fall in sea level. In contrast, in the southern Baltic – including the Polish coast – these movements are substantially weaker or locally take the form of subsidence. As a consequence, these areas are particularly vulnerable to the effects of eustatic global mean sea-level (GMSL) rise, which is reflected in long-term changes in both mean and extreme sea levels (Groh et al., 2017).

The Polish Baltic coast, characterized by diverse coastal morphology and a substantial proportion of both accretionary and erosional segments, represents an area where sea-level change has significant geomorphological as well as socio-economic implications. An increase in mean sea level, combined with variability in storm conditions, affects the frequency and spatial extent of storm surges, the intensity of coastal erosion processes, and the risk of coastal flooding. For this reason, the analysis of long-term sea-level trends along the Polish coast requires consideration of both the global and regional background, as well as site-specific local controls.

The aim of this review paper is to provide a synthetic presentation and discussion of long-term sea-level trends along the Polish Baltic coast in the context of observed and projected changes in the Baltic Sea and the global ocean. The study addresses both changes in mean sea level (MSL) and trends in extreme water levels and storm surges, with particular emphasis on differences in temporal scales and the driving mechanisms underlying the observed variability.

Global ocean sea-level changes in the 20th and early 21st Century

Long-term sea-level trends in the Baltic Sea, as a semi-enclosed basin connected to the global ocean, should be considered in the context of global climate change. A key indicator of these changes is the dynamics of global mean sea level (GMSL). According to the latest report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC AR6, 2023), GMSL has been rising since 1900 faster than during any other century in at least the past 3,000 years. GMSL reconstructions based on tide-gauge records indicate a rise of approximately 21 cm between 1901 and 2020, corresponding to an average rate of 1.7 mm·yr^{-1} (IPCC AR6, 2023; Palmer et al., 2021). Between 1901 and 1971, the mean rate of sea-level rise was 1.3 mm·yr^{-1}, increasing to 1.9 mm·yr^{-1} during 1971–2006. The GMSL rise accelerated to 3.3 mm·yr^{-1} between 1993 and 2018, and further to 3.7 mm·yr^{-1} in 2006-2018 — more than twice the rate observed in the 20th century (IPCC AR6, 2023; IPCC, 2023). Other studies suggest that this acceleration led to a GMSL rise of up to 4.8 mm·yr^{-1} during the last decade (Voosen, 2020).

Since 1970, the dominant driver of accelerated sea-level rise, both globally and in European seas, has been anthropogenic forcing. Initially, ocean thermal expansion due to climate warming was the primary contributor to GMSL increase. However, since around 2000, the mass loss from mountain glaciers and the Antarctic and Arctic ice sheets has exceeded the contribution from thermal expansion (IPCC AR6, 2023; WCRP Global Sea Level Budget Group, 2018). These processes constitute the so-called eustatic sea-level rise.

Projections of global ocean sea-level rise

Future projections indicate continued sea-level rise, depending on greenhouse gas emission scenarios (primarily CO_2, CH_4, and SO_2). By 2100, relative to the 1995-2014 baseline period, GMSL is likely to rise by 0.28–0.55 m under a very low-emission scenario (SSP1–1.9), 0.44–0.76 m under an intermediate-emission scenario (SSP2–4.5), and 0.63–1.01 m under a very high-emission scenario (SSP5–8.5), with a 66% probability. High-risk scenarios involving ice-sheet destabilization could lead to GMSL increases of up to 2.3 m by 2100 and 5 m by 2150, though these outcomes are considered unlikely. The average rate of global sea-level rise is projected to reach approximately 15 mm·yr^{-1} by 2100, and exceed several centimeters per year in the 22nd century (IPCC, 2022). For the remainder of the 21st century, projected ocean warming – depending on emission scenario – is expected to be 2–4 to 4–8 times higher than observed warming during 1971–2018. Unfortunately, these changes in global ocean temperature are irreversible on timescales of centuries to millennia (IPCC, 2023). It is also projected that every five-year delay in reaching peak global greenhouse gas emissions increases the predicted sea-level rise by 2300 by 0.2 m, and the projected extreme (95th percentile) sea-level rise by as much as 1 m (Mengel et al., 2018).

Over longer timescales, as a result of ongoing deep-ocean warming and ice-sheet melt, sea level is expected to rise for centuries to millennia and subsequently remain elevated for thousands of years. Over the next 2,000 years, the global mean sea level (GMSL) is projected to increase by approximately 2–3 m under a 1.5°C warming scenario, 2–6 m under a 2°C scenario, and 19–22 m under a 5°C scenario, after which it will continue to rise over subsequent millennia (IPCC, 2023).

Although the global sea-level rise is pronounced, its rate exhibits strong regional and local variability due to processes such as glacio-isostatic adjustment (GIA), vertical land motion (VLM), changes in ocean circulation, and local climatic mechanisms. In the context of the Anthropocene, these changes are of fundamental importance for coastal zones, including the Baltic Sea coast.

Drivers and timescales of sea-level change in the Baltic Sea

As previously noted, the Baltic Sea is a semi-enclosed, tide-free, intra-continental sea connected to the Atlantic Ocean via narrow and shallow Danish straits. Covering an area of approximately 417,000 km^2 and a volume of around 21,200 km^3, the Baltic Sea contributes only about 0.1% of the global ocean's surface area and volume. Consequently, its direct contribution to global sea-level change is minor (Weisse et al., 2021; Meier et al., 2023). Nevertheless, long-term sea-level trends in the Baltic Sea reflect the global mean sea-level (GMSL) signal.

The Baltic tide-gauge network is one of the densest and longest-operating monitoring systems in the world. Currently, approximately 220 tide gauges are deployed along the Baltic coastlines, meticulously monitoring sea-level variability (Wolski et al., 2025). Within this network, about 50 gauges have been continuously recording for over 60 years (Weisse et al., 2021). Satellite radar altimetry from various missions has been available for the Baltic Sea continuously since 1991 (Schöne et al., 2010).

Water levels in the Baltic Sea change considerably as a complex result of the superposition of multiple global, regional, and local meteorological and hydrological factors, as well as geological processes operating at large spatial scales. Each of these factors is associated with its own characteristic timescale — ranging from minutes, hours, and days, to weekly, seasonal, multi-annual, centennial, and multi-millennial scales (BACC II Author Team, 2015; Wolski, 2017; Weisse et al., 2021; Rutgersson et al., 2022; Elken et al., 2024).

The longest timescales affecting long-term trends in mean sea level (MSL) in the Baltic Sea are centennial to multi-millennial, associated with glacio-isostatic adjustment (GIA) of the Earth's crust in the surrounding regions. On timescales from weekly to multi-decadal, the Baltic Sea MSL is controlled by changes in water volume due to inflow and outflow through the Danish Straits (Gustafsson & Andersson, 2001). This exchange is influenced by local anemobaric conditions, the pressure field over the North Atlantic and the Baltic Sea, as well as the sea level in the North Sea (Kowalewska-Kalkowska, 2012). During prolonged periods of prevailing westerly winds, the Baltic Sea receives inflows from the North Sea, resulting in a rise in sea level. Conversely, during prolonged periods of prevailing easterly winds, sea level decreases due to outflow from the Baltic Sea to the North Sea (e.g. record low sea levels in January–February 2026).

Other factors causing volumetric changes in the Baltic Sea include climatic forcing, i.e., long-term variations in mean wind and temperature, river discharge, as well as precipitation and evaporation (Elken et al., 2024). Long-term sea-level changes are also linked to climate indices such as the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), and other atmospheric circulation patterns. The annual sea-level cycle – reflecting the factors controlling the basin's water balance – is clearly distinguishable due to cyclic atmospheric forcing and river outflow. This cycle is itself subject to long-term variability (Hünicke & Zorita, 2008; BACC II Author Team, 2015; Meier et al., 2022a; Rutgersson et al., 2022)

Storm surges and other weather-driven sea-level oscillations, such as seiches, last from a few hours to several days, redistributing water in the sea significantly above or below mean sea level (MSL) during their occurrence. Extreme storm surges occur under conditions of high sea filling, deep low-pressure systems, and the appropriate alignment of their tracks relative to the coastlines. The occurrence of storm surges in the Baltic directly contributes to the increasing and pronounced trends in extreme sea levels observed along all Baltic coastlines (BACC II Author Team, 2015; Wolski & Wiśniewski, 2021; Rutgersson et al., 2022; Elken et al., 2024).

Long-term trends in relative and absolute sea-level change in the Baltic Sea

As noted above, long-term trends in Baltic Sea level dynamics are primarily associated with isostatic movements of the Baltic coasts and, at the global scale, with eustatic (volumetric) sea-level rise. At the largest temporal and spatial scales, the dominant factor modifying the global sea-level signal in the Baltic region is glacial isostatic adjustment (GIA), i.e., the uplift (deformation) of the land following the last glaciation (approximately 10,000 years ago). GIA is one of the key factors determining RSL change, as it generates vertical land motion, as well as geoid changes and deformation of the ocean floor (Groh et al., 2017). The direction and magnitude of GIA depend on the Baltic subregion. Based on continuous GPS observations from 2001–2008, land uplift has been recorded along the northern Baltic coasts, reaching maximum rates of approximately 8 mm·yr^{-1} in the central Gulf of Bothnia. In contrast, in the southern and south-western Baltic, observed uplift rates are close to zero and below the margin of uncertainty (Groh et al., 2017). For these areas, the opposite process occurs – peripheral subsidence, i.e. the settling of the southern coasts at a rate of 0.5–2.0 mm·yr^{-1} (Uścinowicz, 2003; Harff et al., 2017).

Relative sea level RSL is defined as the height of the sea surface relative to the seabed, and thus to the land, at a given location, estimated using tide gauges (mareographs) (BACC II Author Team, 2015). Tide gauges record RSL relative to the local geodetic height system. Based on data from 50 Baltic tide gauge stations for the period 1901-1990, it was established that RSL trends range from -8.7 mm·yr^{-1} around the Bothnian Bay to +1.5 mm·yr^{-1} along the German Baltic coast (Groh et al., 2017). For some eastern Baltic basins, eustatic sea level rise is comparable to the effect of isostatic movement (e.g., Gulf of Finland, Helsinki or Hamina stations), in contrast to northern basins (Bothnian Bay, Vaasa, Kemi), where the negative total sea level trend (vertical crustal movement together with the eustatic effect) prevails (Johansson et al., 2004, BACC II Author Team, 2015). Table 1 summarizes RSL trend results for various Baltic coasts based on papers published in the last 20 years.

Alongside RSL, there is a definition of so-called absolute sea level (ASL). This is the height of the sea surface at a given location relative to the Earth's centre and it most often reflects volumetric (eustatic) sea level variability. ASL is usually measured using satellite altimetry. Relative sea level (RSL) observed at tide gauges represents the combined effect of absolute sea-level change and vertical land motion at the coast.RSL trends can differ significantly from ASL trends in the Baltic Sea region (BACC II Author Team, 2015).

For the period 1900-1991, based on data from 13 tide gauge stations collocated with GPS receivers and modelled geoid changes, the volumetric ASL trend as a regional estimate for the Baltic Sea was 1.2 mm·yr^{-1} (1.3 mm·yr^{-1} GMSL in 1901-1970 for the world ocean) (Groh et al., 2017). Meanwhile, for most Baltic coasts (including the Polish coast), the ASL trend measured by satellite in 1993-2019 was 3 to 4 mm·yr^{-1}, thus matching the rate of global ocean rise GMSL in this period (3.3 mm·yr^{-1}) (European Environment Agency

Table 1. Trends (mm·yr^{-1}) of long-term relative changes in mean sea level (RSL) for various Baltic coasts (after Wolski, 2017)

Coast	Researchers	Tide gauges with sea level trend value determined for the selected period [mm·yr^{-1}]	
Swedish coast	Novotny et al. (2005)	Furügrund –8.0 (1930–2002)	Ratan –7.6 (1930–2002)
		Landsort –2.5 (1930–2002)	
German coast	Richter et al. (2012)	Wismar +1.43 (1908–2007)	Warnemünde +1.39 (1908–2007)
		Sassnitz +0.63 (1908–2007)	Greifswald +0.98 (1908–2007)
Lithuanian coast	Dailidienė et al. (2006)	Kłajpeda +1.32 (1898–2002)	Nida +2.76 (1961–2002)
Estonian coast	Suursaar and Kullas (2009)	Pärnu (Parnawa) +2.7 (1924–2008)	Ristna +1.7 (1950–2008)
		Narva (Narwa) +1.1 (1899–2008)	Tallinn +1.5 (1899–1995)
Danish coast	Knudsen et al. (2010)	Gedser +1.06 (1900–2000)	Hornbaeck +0.13 (1900–2000)
		Korsør +0.78 (1900–2000)	Frederikshavn –0.42 (1900–2000)
Finnish coast	Johansson et al. (2003)	Kemi –7.30 (1923–1990)	Vaasa –8.0 (1923–1990)
		Mäntyluoto –6.40 (1923–1990	Hanko –3.10 (1923–1990)
		Helsinki –2.50 (1923–1990)	Hamina –2.20 (1923–1990)

2019, IPCC AR6 2023). Very similar ASL trend values for the entire Baltic were proposed by Madsen et al. (2019) based on readings from 57 tide gauge stations, satellite measurements and statistical data reconstruction models. The authors estimated an ASL trend of 1.34 mm·yr^{-1} for the period 1900–1999, 3.4 mm·yr^{-1} for the period 1993–2014 based on the data reconstruction model, and 4.0 mm·yr^{-1} for the period 1993–2015 based on altimetric measurements (Madsen et al., 2019). Other recent altimetric research projects also determine the ASL trend averaged for the entire Baltic at approximately 4.0 mm·yr^{-1} (Łyszkowicz & Bernatowicz, 2018; Passaro et al., 2021; Kapsi et al., 2023). Based on the above calculations, it can easily be concluded that the rate of volumetric changes in Baltic waters (eustatic rise) keeps pace with the rise in the world ocean in the 20th century as well as slightly exceeding it in the last 2 decades of the 21st century.

In the long-term perspective, global mean sea level rise (GMSL) is expected to have the greatest impact on future changes in the Baltic Sea level (BACC II Author Team 2015; Weisse et al., 2021). It is predicted that most of the future absolute sea level rise ASL in the Baltic will be strongly linked to corresponding, large-scale changes in the North Atlantic and factors modulating these changes. These factors are mainly thermal expansion of the water column, the influence of Antarctic ice sheet melting (BACC II Author Team 2015, Meier et al., 2022b) and the influence of variability and changes in the meridional circulation of the Atlantic Ocean (Börgel et al., 2018).

Factors controlling sea-level change along the Polish coast

The length of the Polish sea coast is 498 km (without the shoreline of the Vistula and Szczecin Lagoons) (Dobracki & Uścinowicz, 2007). 80% of this length can be classified as dune coastlines, with dune heights from several metres to over 40 m. Meanwhile, cliffs with heights ranging from a few to several tens of metres above sea level constitute approximately 20% of the Polish coastline (Musielak et al., 2017). The factors determining the direction and rate of coastline changes in the southern part of the Baltic Sea, apart from hydrodynamic processes such as currents and wind waves, are primarily sea level fluctuations (Cieślikiewicz & Paplińska-Swerpel, 2008; Jędrasik 2014).

Similarly to most Baltic coasts, sea level and water fluctuations in the Polish coastal zone have various causes and amplitudes as well as differ in duration. The impact of sea levels on the coastal zone is also spatially variable (Musielak et al., 2017). The basic factor when considering long-term trends of sea level changes, similarly to the northern Baltic coasts, are geological causes and in particular the aforementioned subsidence processes. In contrast to the regressive, northern parts of the Baltic Basin (where GIA compensates for eustatic rise), on the southern, transgressive Baltic coasts glacio-isostatic subsidence and eustatic rise have the same direction and complement each other, causing permanent flooding and consequently permanent retreat of the coastline towards land (Harff et al., 2017). The Polish coast is divided into 2 zones associated with subsidence with a tendency to lowering (1– Świnoujście to Darłowo, 2 – Gulf of Gdańsk) and one zone with a tendency to uplift (Darłowo-Puck). Neotectonic (geological) processes occurring in these zones, depending on their character, enhance (subsidence) or reduce (uplift) the morphodynamic effects of marine transgression and simultaneously influence relative sea level fluctuations. These processes are noticeable both on a timescale measured in millennia and on a spatial scale covering hundreds of kilometres of coastline (Musielak et al., 2017).

Long-term trends in mean sea level along the Polish Baltic coast

Water level measurements on the Polish coast are currently operated by 13 tide gauges from Świnoujście in the western part (Usedom Island) to Nowy Świat in the eastern part of the coast (Vistula Spit), administered by the Institute of Meteorology and Water Management (Fig. 1) (Hydro IMGW-PIB 2025). It is worth noting that the tide gauge in Świnoujście, which has a measurement series of mean sea levels from 1811, is the 3rd oldest tide gauge on the Baltic Sea (after Stockholm 1774 and Kronstadt 1777), and at the same time the only one that has remained operational since the beginning of the 19th century, with only a minor interruption in 1945-1946 due to wartime and post-war circumstances. (Bogdanov et al., 2000; Ekman, 2009; Kowalewska-Kalkowska & Marks, 2011). This series was used to determine time intervals on a decadal scale where accumulation occurred in the coastal zone as sea level lowered by several centimetres on average, as well as longer periods of coastal erosion with fluctuating rise of mean sea level (Musielak, et al., 2017). The mean relative sea level rise over the last 200 years in Świnoujście was 20 cm at a rate of 1 mm·yr^{-1} (Kowalewska-Kalkowska & Marks, 2011). However, due to the significantly shorter operating time of the remaining tide gauges on the Polish coast, most estimates of long-term sea level trends fall within the time interval from 20 to 70 years. Below are compiled estimates of trends in mean relative sea level along the Polish coast published in the last 30 years by various researchers (Tab. 2).

Based on the compiled trend results, it can be stated that an increasing trend in relative mean sea levels occurs along the entire Polish coast, which from the mid-20th century has been increasing at a rate of 2 mm·yr^{-1}, i.e. an average of 15 cm over the last 75 years. This increase is faster compared to the end of the 19th century and the first half of the 20th century. This sea level rise is attributable not only to global factors (GMSL rise) but also to the aforementioned neotectonic processes on the Polish coast as well as processes responsible for the intensification of westerly circulation in the second half of the 20th century (Moberg et al., 2005; Jakusik et al., 2012). Miętus et al. (2004) explains the increase in mean as well as maximum sea level (95th percentile, Table 2) by the increased intensity

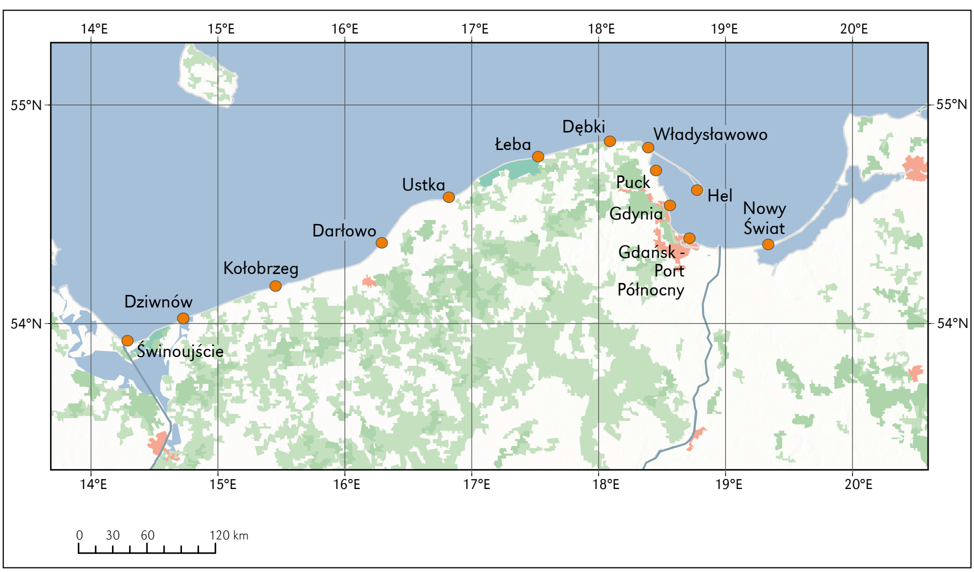


Figure 1. Tide gauges on the Polish coast administered by the Institute of Meteorology and Water Management

Source: Own elaboration based on Hydro IMGW-PIB 2025.

Table 2. Trends ($mm\cdot yr^{-1}$) of long-term, relative changes in mean sea level (RSL), minimum levels (5th percentile) and maximum levels (95th percentile) for the Polish coast in the 19th-21st centuries

Tide gauges	Dziadziuszko & Jednorał (1988)		Rotnicki & Borzyszkowska (1999)			Jakusik et al. (2012)					Łyszkowicz & Bernatowicz (2019) Period: 1951-2017	Klimat Polski (2024) Period: 1950-2024
	period:		period:			period: 1951-2008						
						year						
	1883 -1985	1951 -1985	1951 -1990	1951 -1970	1971 -1990	averaged trend	perc. 5%	perc. 95%	winter	summer		
Świnoujście	1.1	1.4	2.01	2.27	4.23	1.7	0.7	2.9	1.9	1.5	1.82	1.99
Kołobrzeg	1.3	0.8	1.94	0.80	5.25	1.8	1.3	2.5	2.3	1.2	1.70	
Ustka	0.6	2.0	2.58	0.79	3.95	2.0	1.3	2.8	2.5	1.6	1.92	
Łeba						1.6	0.9	2.7	2.2	1.3	1.35	
Władysław.						2.4	2.4	2.6	3.2	1.8	1.99	2.24
Hel		1.7				1.7	1.1	2.5	2.4	1.2	1.34	
Gdynia						2.3	1.9	3.0	3.1	1.8		
Gdańsk Port	1.5	2.9	3.76	1.87	6.99	2.8	2.8	2.8	3.6	2.2		

and stability of western air masses, which are pushed with greater force from the North Sea into the Baltic, whilst the opposite direction of advection favours sea level lowering (outflow of waters from the basin) occurring much less frequently. The result of these processes is also the sea surface slope along the Polish coast from west to east with the dominance of zonal, westerly air mass circulation (Miętus et al., 2004, Jakusik et al., 2010, Klimat Polski, 2024). It is worth noting that the RSL trend value during the year is highest in winter and partially in spring, and lowest in the summer months. This is understandable, as winter is the period of the year with the greatest intensity of westerly circulation and the positive phase of the North Atlantic Oscillation (Wolski, 2017). It should be noted that the absolute sea level (ASL) trend for Polish coastal stations (from Świnoujście to Gdańsk) measured by satellite altimetry during the period 1993-2017 and corrected for glacial isostatic adjustment (GIA) averaged 3.7 $mm\cdot yr^{-1}$– nearly twice as high as the relative sea level (RSL) trend measured since the mid-20th century (Pająk & Błaszczak-Bąk, 2019).

Trends in maximum sea levels and storm surges long the Polish coast. Changes in return periods

It follows from Table 2 that trends in maximum sea level rise (95th percentile) on the Polish coast are clearly higher than trends in mean sea levels (on average 2.7 : 2.0 $mm\cdot yr^{-1}$). In the winter period, the trend of maximum sea levels is even greater than the annual average and ranges from 3.3 $mm\cdot yr^{-1}$ in Świnoujście to 4.3 in Gdańsk (Jakusik et al., 2012). This corresponds with the results of the Institute of Meteorology and Water Management report – Klimat Polski (2024), according to which in the years 1961-2024, in both the western and eastern parts of the Polish coast, a progressive decade to decade decrease in the number of cases of low water levels is observed, particularly strong in Świnoujście. At the same time, an increase in the number of cases of levels higher than the mean occurs, in particular up to alarm level values (Tab. 3).

On the other hand, studies by Sztobryn et al. (2012) indicate that on the Polish coast (Świnoujście, Ustka, Hel stations)

Table 3. Frequencies of water levels below mean level and above alarm level in individual decades at the Świnoujście and Władysławowo tide gauges. (Klimat Polski, 2024)

Świnoujście	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	2011-2020
Below mean level [%]	0.000	0.028	0.000	0.027	0.000	0.082
Above alarm level [%]	0.137	0.110	0.084	0.055	0.219	0.250
Władysławowo						
Below mean level [%]	0.082	0.547	0.027	0.109	0.055	0.082
Above alarm level [%]	0.110	0.164	0.465	0.328	0.549	0.411

the frequency of occurrence of maximum sea levels during storm surges clearly increased in the period 1981-2008 compared to the period 1955-1980. Confirmation of the above regularities not only on the Polish coast are also other interrelated long-term processes – increase in the duration of high sea levels, increase in the number of storm surges and change in the return period (recurrence interval) of maximum levels. Table 4 summarises the results of trends in the duration of high levels (≥ 70 cm) and trends in the number of storm surges in the period 1960-2010 (Wolski, 2017).

Table 4 shows a more than twofold increase in the number of hours of high sea levels (≥ 70 cm) and a nearly twofold increase in the average annual number of storm surges on the Polish coast between 1960 and 2010. Similar trends, although with lower intensity, occur on the remaining Baltic coasts. For the extended period 1960-2020, the number of hours with high levels on all Baltic Sea coasts increased on average from 71 to 98 hours, and the number of storm surges from 3.1 to 5.5 (Wolski & Wiśniewski, 2021). Other studies concerning the occurrence of storm surges in the Polish coastal zone in various time ranges confirm the increasing trend in the number and intensity of storms from the mid-20th century (Rotnicki & Borzyszkowska, 1999; Sztobryn et al., 2005, 2012; Wiśniewski & Wolski, 2009; Przygrodzki & Letkiewicz, 2015; Kowalska & Kubicka, 2020). According to Sztobryn et al., (2012), the threat of storm surges on the southern Baltic increased almost twofold at the end of the 20th century compared to the mid-20th century. In the period 1950-1979, 72 storms occurred, whilst in 1980-2008 as many as 129. There was also a shift in the highest frequency of storm occurrence from November to January. Additionally, on the western coast in the last quarter of the 20th century, an increase in the frequency of occurrence of very high storm surges (with a maximum above 140 cm of the tide gauge zero) was observed, with a simultaneous decrease in storm surges with maximum sea level values of around 70 cm (Sztobryn et al., 2012). On the other hand, other studies indicate a more than 3-fold increase in the number of storms on the Polish coast, from 107 in the decade 1960-1969 to 367 in the decade 2000-2009 (Przygrodzki & Letkiewicz, 2015). These authors provide the total

Table 4. Trends in the annual number of hours with high sea levels (≥ 70 cm) and in the annual number of storm surges at tide gauge stations along the Polish coast, derived from regression lines for the beginning and end of the 1960–2010 period (Wolski, 2017)

Tide gauges	Long-term increase in the number of hours with high sea levels	Long-term increase in the number of storm surges
Świnoujście	**23→69**	**1.9→3.8**
Kołobrzeg	**33→68**	1.9→3.3
Ustka	**27→61**	1.3→2.3
Władysławowo	18→63	1.8→2.8
Gdańsk	**30→96**	**1.3→3.0**
Polish coast (average)	26→71	1.6→3.0

*bold font indicates statistical significance at the $\alpha = 0.05$ level number of storms at individual stations in the period 1960-2010: 212 in Świnoujście, 228 in Kołobrzeg, 210 in Ustka, 156 in Hel, 220 in Gdynia and 253 in Gdańsk. The duration of surges also lengthened and the heights of surges above alarm levels increased in the period 1960-2010 (Przygrodzki & Letkiewicz, 2015).

A process parallel to the rise in extreme sea levels and the increasing number of storm surges in the long term is the effect of shortening of the return period (recurrence) in the course of occurrence of the highest annual water levels of the Baltic Sea. In Figure 2, the differences in theoretical water height between the period 1960-2020 and the period 1900-1960 are presented for 2 tide gauge stations Świnoujście and Gdańsk. Theoretical water is determined on the basis of the series of maximum annual sea levels using statistical probability distributions employed in hydrology. Thanks to this, it is known with what frequency a given water level may occur,

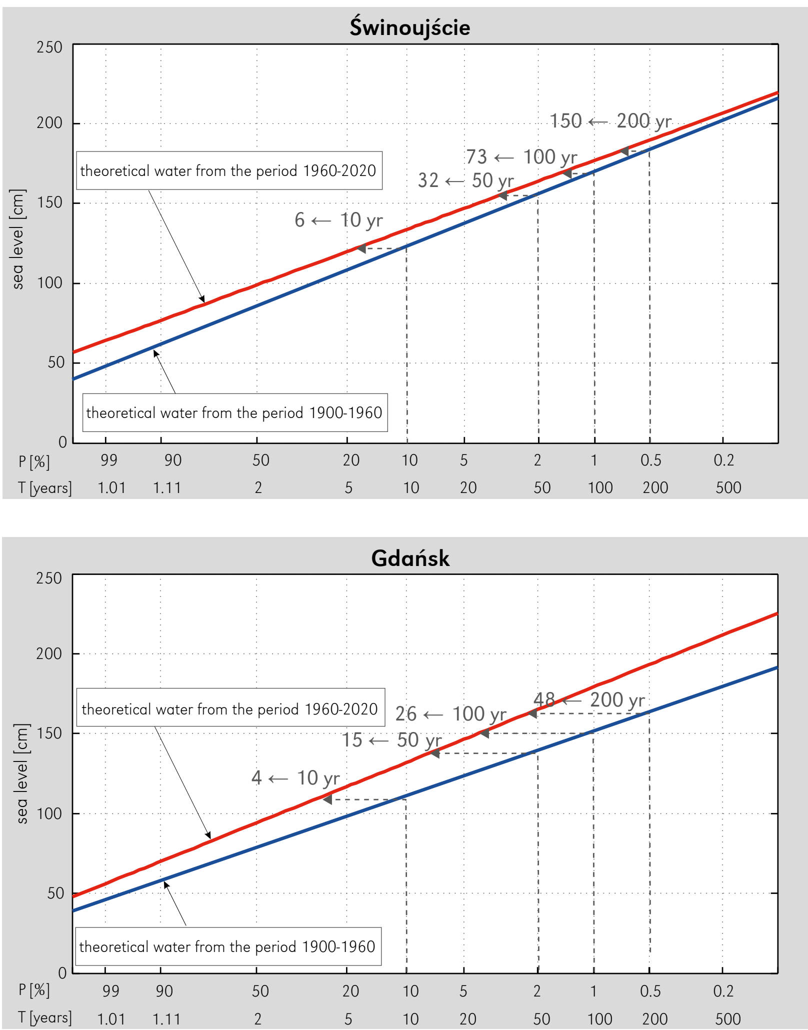


Figure 2. Differences in theoretical water levels between 1900–1960 and 1960–2020 for Świnoujście and Gdańsk tide gauges

e.g. once in 10 years – so-called 10-year water, or once in 100 years, so-called 100-year water. Such probabilistic estimates are needed for coastal zone engineering, siting of hydraulic structures, determining the crest elevations of port quays and flood protection embankments. Comparing the two stations, the theoretical water level was read for: 200-year, 100-year, 50-year and 10-year water for both time ranges.

It follows from Figure 2 that at both tide gauge stations, the theoretical water level from the period 1960-2020 always exceeded the theoretical water level from the period 1900-1960 across the full range of quantiles (from 0.1 to 99%). This indicates a constant increase in theoretical and thus observed maximum annual sea levels in both Świnoujście and Gdańsk in the second half of the 20th century and at the beginning of the 21st century. At the same time, the return period for these tide gauges was significantly reduced. For example, for Świnoujście, the 100-year water after 60 years decreased to 73-year water, and the theoretical water level rose during this time from 171 to 177 cm. Meanwhile, in Gdańsk, the 100-year water shortened to 26-year water, and the theoretical water level rose in the same period from 152 to 179 cm (Wolski et al., 2025). Averaging all ranges of reduction in theoretical water level for both tide gauge stations, it can be established that the return period of maximum annual sea levels on the Polish coast over the last 60 years has shortened on average by 50%, which is a result identical to the averaged reduction of return period for tide gauges of all Baltic coasts in the same period 1960-2020 (Wolski et al., 2025). It can therefore be inferred that hydrological hazards in the Baltic Sea region and on the Polish coast during the last 60 years, in the main period of the Anthropocene, appeared twice as frequently as in the first half of the 20th century.

Analysing sea level trends on the Polish Baltic coast from the mid-20th century, an increase in mean and maximum sea level, an increase in the duration of high water levels, an increase in the number of storm surges and a reduction in the return period of the highest annual sea levels can be observed. These are processes that occur with greater or lesser intensity on all coasts of the Baltic Sea (BACC II Author Team, 2015; Wolski, 2017; Wolski et al., 2021; Rutgersson et al., 2022). As already mentioned, the causes of such a picture are multi-scale and multi-directional. According to recent IPCC reports, the main cause (although not the only one) of the rise in mean and maximum water levels in the Baltic and peripheral seas is the global rise in the world ocean level (GMSL), i.e. eustatic rise generated by climate changes in the Anthropocene (IPCC AR6, 2023; IPCC 2023). For the Polish coast, this eustatic rise is intensified by neotectonic movements of coastal subsidence, which triggers transgression processes of the sea and creates preconditions for flooding of the coastal zone during storm periods (Harff et al., 2017). It should be emphasised that the greatest changes in the Polish coastal zone are observed especially during most storm surges lasting 1-3 days, with wind from north-west to north-east and water levels exceeding 60 cm (Musielak et al., 2017). Superimposed on this are mechanisms related to the intensification of zonal westerly circulation on a regional and local scale, strengthening of NAO especially in the winter period, which causes periodic fillings of the Baltic basin and systematic sea level rise on the Polish coast (Heyen 1996, Miętus 2004, BACC II Author Team, 2015; Girjatowicz 2007; Jakusik et al., 2010, 2012). According to Rotnicki and Borzyszkowska (1999), the more frequent occurrence of high levels (storm surges) on the Polish Baltic coast is indirectly due to global causes (GMSL rise) and directly to changes in the frequency of occurrence of specific circulation patterns. These two processes constitute a specific positive feedback consisting in the fact that sea level rise increases the frequency of storm surges, whilst on the other hand, the increase in storm surges caused by changes in atmospheric circulation affects the rise in mean sea level.

Projections of sea-level rise along the Polish coast in the 21st Century

Most European coasts, including the Polish Baltic coast, are experiencing a rise in both absolute sea level ASL and relative sea level RSL, with the latter being of greater significance for coastal protection (Komunikat PAN, 2021). Therefore, in Figure 3 and Table 5 projections of relative sea level change RSL for tide gauge stations of the Polish coast for the year 2050 and the year 2100 are compiled based on greenhouse gas emission scenarios from the latest IPCC report (IPCC AR6 Sea Level Projection Tool, 2025).

According to data contained in Table 5 and Figure 3, the projected mean sea level rise on the Polish coast in 2050 may range from 20-24 cm (very low emissions scenario, SSP1–1.9) to 26-30 cm (very high emissions scenario SSP5–8.5) relative to the mean of 1995-2014. In 2100, sea level rise may amount to 39-46 cm (SSP1–1.9 scenario) to 79-87 cm (SSP5–8.5 scenario). Unfortunately, in light of the latest IPCC scenarios, the Polish coast appears as one of the most threatened on the Baltic Sea alongside the coasts of Lithuania, Germany and Denmark (IPCC AR6 Sea Level Projection Tool, 2025). This is confirmed by the CMIP6 multi-model forecast (Coupled Model Intercomparison Project Phase 6), an international climate model research project, according to which, in the very high emissions scenario (SSP5–8.5), the southern Baltic coasts will experience by the end of the 21st century the fastest relative sea level rise RSL in the basin, amounting to 6-7 mm·yr^{-1} (Fig. 4; European Environment Agency, 2025 a).

The differences in sea level rise between individual Polish tide gauge stations are small, amounting to a few centimetres, but for the Polish coast there is a noticeable trend in the observed RSL values – i.e., an increase in sea level forecasts from west to east.

According to European Environment Agency (2025b), a 10 cm sea level rise usually causes approximately a tenfold increase in the frequency of occurrence of floods of a certain height. IPCC projections indicating over 20 cm sea level rise on the Polish coast even by 2050 show a large scale of flood hazard. According to CMIP6, in the low emissions SSP scenario, coastal floods which historically occurred once in 100 years will occur ten times more frequently on all European coasts by the end of the century. In the high emissions SSP scenario, it is projected that coastal floods occurring once in 100 years will occur at least once a year along most European

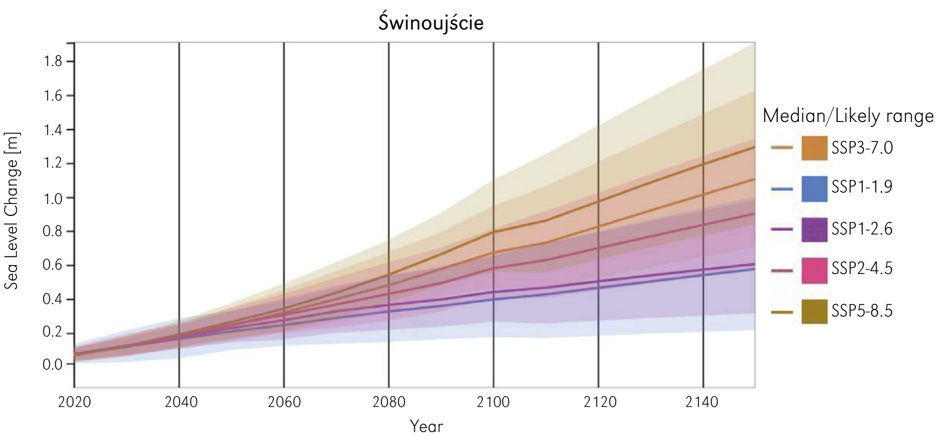


Figure 3. Projections of mean sea level rise on the Polish coast – Świnoujście tide gauge until the year 2140 based on the latest IPCC report (IPCC AR6 Sea Level Projection Tool, 2025), Creative Commons Attribution 4.0 International License

Table 5. Projections of relative, mean sea level change RSL (median) for tide gauge stations of the Polish coast for the year 2050 and the year 2100 based on scenarios from the latest IPCC AR6 report relative to the mean of 1995-2014 (IPCC AR6 Sea Level Projection Tool, 2025), Creative Commons Attribution 4.0 International License

Tide gauges	SSP1–1.9*		SSP1–2.6		SSP2–4.5		SSP3–7.0		SSP5–8.5	
	in 2050	in 2100	in 2050	in 2100	in 2050	in 2100	in 2050	in 2100	in 2050	in 2100
Świnoujście	21 cm	40 cm	23 cm	44 cm	25 cm	58 cm	24 cm	67 cm	26 cm	79 cm
Kołobrzeg	20 cm	39 cm	23 cm	43 cm	24 cm	57cm	24 cm	67 cm	26 cm	79 cm
Ustka	21 cm	41 cm	23 cm	45 cm	25 cm	59 cm	25 cm	69 cm	27 cm	81 cm
Władysławowo	23 cm	44 cm	25 cm	49 cm	27 cm	63 cm	27 cm	72 cm	29 cm	85 cm
Hel	23 cm	44 cm	25 cm	49 cm	27 cm	63 cm	27 cm	73 cm	29 cm	85 cm
Gdańsk	24 cm	46 cm	26 cm	51 cm	28 cm	65 cm	28 cm	75 cm	30 cm	87 cm

*SSP (Shared Socio-economic Pathway) scenarios used in IPCC AR6 reports describe socio-economic trends and are associated with levels of greenhouse gas emissions (Nauka o Klimacie, 2021):

SSP1–1.9 – very low emissions scenario with emissions rapidly falling to zero in the middle of the century, followed by large-scale CO_2 removal from the atmosphere; (temperature rise 1.4–1.6°C by 2100)

SSP2–2.6 – low emissions scenario similar to SSP1–1.9, but with slower emission decline, later achievement of net zero emissions and lower level of CO_2 removal from the atmosphere (temperature rise 1.7–1.8°C by 2100)

SSP2–4.5 – intermediate emissions scenario with greenhouse gas emissions remaining until the second half of the century at a level close to the present, then gradually falling, but not below zero until the end of the 21st century (temperature rise ~2.7°C by 2100)

SSP3–7.0 – high emissions scenario in which emissions rise, doubling relative to the current level by the end of the century; (temperature rise ~3.6°C by 2100)

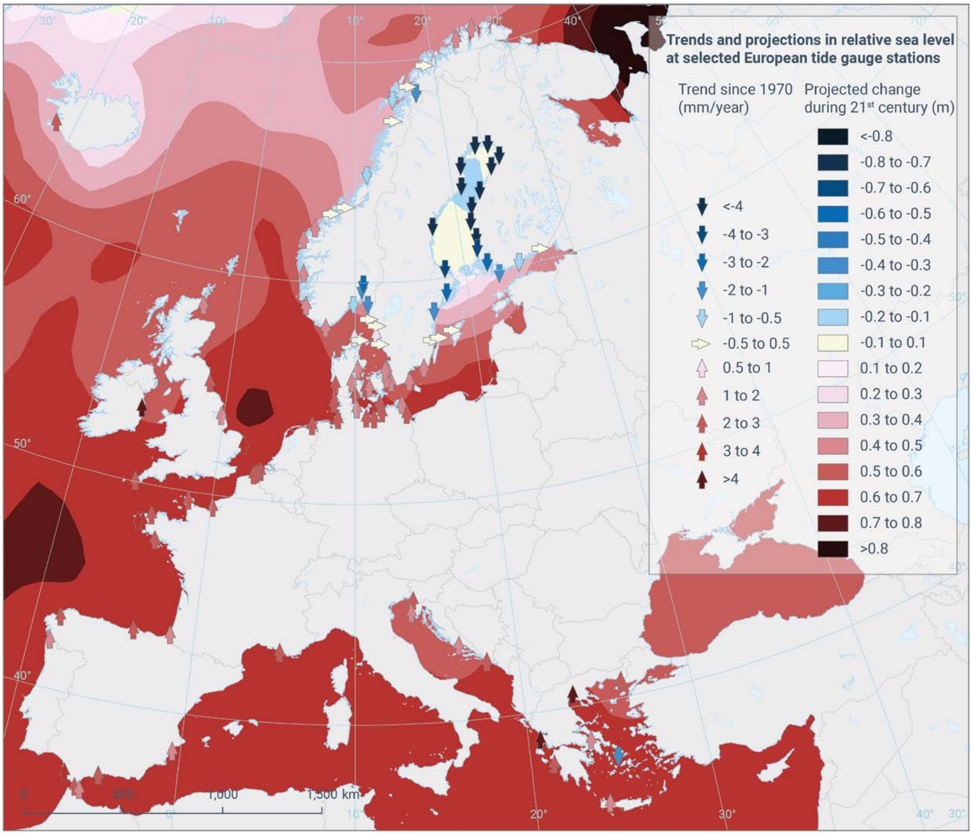
SSP5–8.5 – very high emissions scenario in which emissions rise rapidly, doubling relative to the current level by the middle of the century (temperature rise ~4.4°C by 2100)

coasts before 2050 (European Environment Agency (2025 b).

Such projections have significant consequences for the shape of the Polish coast: intensification of cliff and sandy shore erosion is possible, migration of the coastline towards land, and increased storm flood hazard. A considerable sea level rise causes the wave energy dissipation zone to shift towards land, so that wave breaking may reach the foot of the dune or cliff, causing significant erosion there (Musielak et al., 2017). Weisse et al. (2021) emphasises that changes in wind and wave climate may additionally increase erosion risk and affect sedimentation. Therefore, work is being carried out in Poland aimed at identifying areas threatened from the sea side due to predicted climate changes. One such project is flood risk maps and flood hazard maps made available by the state institution – Polish Waters on the Hydroportal within the IT System for Country Protection (ISOK 2025). According to these maps, the most flood-threatened regions are: the coasts of the Vistula Lagoon, the Vistula estuary, the Oder estuary area together with the coasts of the Szczecin Lagoon and Kamieński Lagoon, as well as areas around coastal lakes: Łebsko, Gardno, Wicko, Bukowo, Jamno, Resko. River mouths of Pomerania to the Baltic are also places threatened by storm floods.

Conclusions

- Sea level changes on the Polish coast registered in the main period of the Anthropocene, i.e. from the mid-20th century to the beginning of the 21st century, are distinct. During this time, relative sea level rose on average by 15 cm (at a rate of ~2 $mm \cdot yr^{-1}$). This is a result of the rise in global mean



Reference data: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO

Figure 4. Current trends and projected changes in relative sea level in Europe (European Environment Agency, 2025a).

Source: European Commission, European Environment Agency (EEA) (https://www.eea.europa.eu/legal/copyright)

sea level (GMSL), i.e. eustatic rise generated by climate changes and increasing anthropopression, as well as coastal subsidence processes. Both these factors, although multi-scale, have the same direction and complement each other, triggering transgression processes of the sea and creating preconditions for flooding of the coastal zone during storm periods. Superimposed on this are mechanisms related to the intensification of zonal westerly circulation on a regional and local scale, which causes additional sea level rise and steadily increasing flood hazard of areas situated along the Polish coast.

- The relative increase in average sea level on the Polish coast is accompanied by more dynamic increases in maximum sea levels, longer duration of these events, and intensifying processes of storm surge frequency and intensity since the mid-20th century. This, in turn, results in increased coastal erosion and sediment transport, as well as an increase in the frequency of storm surges. At the same time, over the last 60 years, the return period of the highest annual sea levels has been reduced by about 50%, which indicates that hydrological hazards in the Baltic Sea region and on the Polish coast occurred twice as often during this period than in the first half of the 20th century, which is also a result of human-induced climate change.

- Projections from a credible international institution such as the Intergovernmental Panel on Climate Change (IPCC) are deeply alarming for the Polish coast and Polish administration. The Projections in the latest IPCC report for 2050 indicates a rise of 20-24 cm (low greenhouse gas emission scenario) and 26-30 cm (very high emission scenario) relative to the average from 1995-2014. Meanwhile, by 2100, sea level rise may reach 39-46 cm (low emission scenario) to 79-87 cm (high emission scenario) compared to the 1995-2014 average. Such increases indicate an unprecedented acceleration in mean sea level in the current century, potentially reaching 6-7 $mm \cdot yr^{-1}$ – more than three times higher than from the mid-20th century to present – which further increases the risk of erosion and storm floods. This is particularly possible when large ice sheets in Antarctica and the Arctic melt faster. In light of the above data, the Polish coast appears to be one of the most hydrologically threatened areas in the entire Baltic Sea region.
- Any long-term change in mean or extreme sea level, as well as coastal erosion, will have an immediate impact on society, affecting sectors such as: coastal protection, coastal navigation, and the development of marine renewable energy sources.
- The latest alarming sea level rise projections for the Polish coast indicate the necessity of deep adaptation to climate change – particularly in depression areas and large agglomerations. Key actions must be undertaken: monitoring, incorporating dynamic forecasts and IPCC projections into spatial planning and investment in coastal zones, as well as effective and dynamic infrastructural coastal protection.
- Further research is needed integrating models of isostasy, extreme hydrodynamic events, sedimentation, and coastal erosion to better understand and predict future coastal topography under climate change conditions.

Acknowledgements

Cofinanced by the Minister of Science under the "Regional Excellence Initiative" Program for 2024-2027 (RID/SP/0045/2024/01).

I dedicate this article to the memory of my academic mentor, Professor Bernard Wiśniewski, a long-standing and highly regarded lecturer at the Szczecin Maritime University and the University of Szczecin, for whom the issue of sea-level change was one of his main areas of research interest.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

References

BACC II Author Team (Eds.). (2015). *Second assessment of climate change for the Baltic Sea Basin*. Regional Climate Studies. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-16006-1

Bogdanov, V. I., Medvedev, M. Y., Solodov, V. A., Trapeznikov, Y. A., Troshkov, G. A., & Trubitsina, A. A. (2000). *Mean monthly series of sea level observations (1777–1993) at the Kronstadt Gauge*. Reports of the Finnish Geodetic Institute. Kirkkonummi: Finnish Geodetic Institute.

Börgel, F., Frauen, C., Neumann, T., Schimanke, S., & Meier, H. E. M. (2018). Impact of the Atlantic multidecadal oscillation on Baltic Sea variability. *Geophysical Research Letters*, *45*(18), 9880-9888. https://doi.org/10.1029/2018GL078943

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., … & Unnikrishnan, A. S. (2013). *Sea level change*. PM Cambridge University Press.

Cieślikiewicz, W., & Paplińska-Swerpel, B. (2008). A 44-year hindcast of wind wave fields over the Baltic Sea. *Coastal Engineering*, *55*(11), 894-905. https://doi.org/10.1016/j.coastaleng.2008.02.017

Dailidienė, I., Davulienė, L., Tilickis, B., Stankevičius, A., & Myrberg, K. (2006). Sea level variability at the Lithuanian coast of the Baltic Sea. *Boreal Environment Research*, *11*, 109-121.

Dobracki, R., & Uścinowicz, S. (2007). Geozagrożenia polskiego brzegu Bałtyku. *Przegląd Geologiczny*, *55*(8), 639-640.

Dziadziuszko, Z., & Jednorał, T. (1988). Wahania poziomów morza na polskim wybrzeżu Bałtyku. *Studia i Materiały Oceanologiczne* 52, *Dynamika Morza* 6, 215-238.

Ekman, M. (2009). *The changing level of the Baltic Sea during 300 years: A clue to understanding the Earth*. Aland Islands: Summer Institute for Historical Geophysics.

Elken, J., Barzandeh, A., Maljutenko, I., & Rikka, S. (2024). Reconstruction of Baltic gridded sea levels from tide gauge and altimetry observations using spatiotemporal statistics from reanalysis. *Remote Sensing*, *16*(15), 2702. https://doi.org/10.3390/rs16152702

European Environment Agency. (2019; accessed December 2025). Trend in absolute sea level across Europe based on satellite measurements, 1993-2019. https://www.eea.europa.eu/en/analysis/maps-and-charts/trend-in-absolute-sea-level

European Environment Agency. (2025a; accessed December 2025). Past trend and projected change in relative sea level across Europe. https://www.eea.europa.eu/en/analysis/indicators/global-and-european-sea-level-rise-1764145665/past-trend-and-projected-change

European Environment Agency. (2025b; accessed December 2025). Extreme sea levels and coastal flooding in Europe. https://www.eea.europa.eu/en/analysis/indicators/extreme-sea-levels-and-coastal-flooding?activeAccordion=ecdb3bcf-bbe9-4978-b5cf-0b136399d9f8#footnote-WKSFX8AH

Girjatowicz, J. P. (2007). The North Atlantic Oscillation influence on the Odra river estuary hydrological conditions. *Estuarine Coastal and Shelf Science*, *74*, 395-402. https://doi.org/10.1016/j.ecss.2007.04.037

Groh, A., Richter, A., & Dietrich, R. (2017). Recent Baltic Sea level changes induced by past and present ice masses. In: Coastline changes of the Baltic Sea from south to east: Past and future projection (pp. 55-68). Cham: Springer International Publishing.

Gustafsson, B. G., & Andersson, H. C. (2001). Modeling the exchange of the Baltic Sea from the meridional atmospheric pressure difference across the North Sea. *Journal of Geophysical Research: Oceans, 106*(C9), 19731-19744. https://doi.org/10.1029/2000jc000593

Harff, J., Deng, J., Dudzińska-Nowak, J., Fröhle, P., Groh, A., Hünicke, B.,. & Zhang, W.(2017). What Determines the Change of Coastlines in the Baltic Sea?. In J. Harff, K. Furmańczyk, K., & von Storch, H. (Eds.), *Coastline Changes of the Baltic Sea from South to East* (pp. 15-35). Coastal Research Library, vol. 19. Cham: Springer. https://doi.org/10.1007/978-3-319-49894-2_2

Heyen, H., Zorita, E., & von Storch, H. (1996). Statistical downscaling of monthly mean North Atlantic air-pressure to sea-level anomalies in the Baltic Sea. *Tellus A: Dynamic Meteorology and Oceanography,* 48A, 312-323. https://doi.org/10.3402/tellusa.v48i2.12062

Hünicke, B., Zorita, E., Soomere, T., Madsen, K. S., Johansson, M., & Suursaar, Ü. (2015). Recent Change – Sea Level and Wind Waves. In The BACC II Author Team, (Eds.), *Second Assessment of Climate Change for the Baltic Sea Basin*. Regional Climate Studies. Cham: Springer. https://doi.org/10.1007/978-3-319-16006-1_9

Hünicke, B.; Zorita, E (2008). Trends in the amplitude of Baltic Sea level annual cycle. *Tellus A: Dynamic Meteorology and Oceanography*, *60*, 154-164. https://doi.org/10.1111/j.1600-0870.2007.00277.x

Hydro IMGW-PIB. (2025; accessed November 2025). https://hydro.imgw.pl/#/map?sh=true&she=true&lo=18.0663&la=54.7288&zo=7.543987073736913&bl=hydro&tstp=24&omt=1

IPCC. (2022). Summary for Policymakers. In *Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/9781009157964.001

IPCC. (2023). Summary for policymakers. In *Climate change 2021: The physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. https://doi.org/10.1017/9781009157896.001

IPCC AR6. (2023). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896

IPCC AR6 Sea Level Projection Tool. (2025; accessed November 2025). https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool

ISOK. (2025; accessed December 2025). https://isok.gov.pl/hydroportal.html

Jakusik, E., Wójcik, R., Pilarski, M., Biernacik, D. M. M., & Miętus, M. (2012). Poziom morza w polskiej strefie brzegowej – stan obecny i spodziewane zmiany w przyszłości. In *KLIMAT*: '*Wpływ zmian klimatu na środowisko, gospodarkę i społeczeństwo (zmiany, skutki i sposoby ich ograniczania, wnioski dla nauki, praktyki inżynierskiej i planowania gospodarczego)*'. zadanie 6 (pp. 146-169).

Jakusik, J., Wójcik, R., Biernacik, D., Pilarski, M., Miętus, M., & Wójcik, R. (2010). Zmiany poziomu morza wzdłuż polskiego wybrzeża Morza Bałtyckiego. Rezultaty projektu KLIMAT. In E. Bednorz, & L. Kolendowicz (Eds.), *Klimat Polski na tle klimatów Europy. Zmiany i ich konsekwencje* (pp. 219-234). Poznań: Bogucki Wydawnictwo Naukowe.

Jędrasik, J. (2014). *Modelowanie retrospektywne i prognozowanie hydrodynamiki Morza Bałtyckiego*. Gdańsk: Wydawnictwo Uniwersytetu Gdańskiego.

Johansson, M., Kahma, K., & Boman, H. (2003). An improved estimate for the long-term mean sea level on the Finnish coast. *Geophysica*, *39*(1-2), 51-73.

Johansson, M., Kahma, K., Boman, H., & Launiainen, J. (2004). Scenarios for sea level on the Finnish coast. *Boreal Environment Research*, *9*, 153-166.

Kapsi, I., Kall, T., & Liibusk, A. (2023). Sea level rise and future projections in the Baltic Sea. *Journal of Marine Science and Engineering*, *11*(8), 1514. https://doi.org/10.3390/jmse11081514

Klimat Polski. (2024; accessed November 2025). Raport Instytutu Meteorologii i Gospodarki Wodnej. https://imgw.pl/wp-content/uploads/2025/07/RAPORT-IMGW-PIB-Klimat-Polski-2024.pdf

Knudsen, P., Andersen, O., Sørensen, C., & Vognsen, K. (2010; accessed December 2025). Spatial variability in sea level rise and storm surge levels along the Danish coastline, Storm Surges Congress, Hamburg, Germany, 13-17 September 2010, 1-19. https://meetingorganizer.copernicus.org/SSC2010/SSC2010-108.pdf

Komunikat PAN. (2021; accessed November 2025). Komunikat interdyscyplinarnego Zespołu doradczego do spraw kryzysu klimatycznego przy prezesie PAN na temat zmiany klimatu i wzrostu poziomu morza. https://bip.pan.pl/artykul/159-462-zmiany-klimatu-a-wzrost-poziomu-morza-komunikat-02-2021-z-26-stycznia-2021

Kowalewska-Kalkowska, H. (2012). *Rola wezbrań sztormowych w kształtowaniu ustroju wodnego układu dolnej Odry i Zalewu Szczecińskiego.* Wydawnictwo Naukowe Uniwersytetu Szczecińskiego.

Kowalewska-Kalkowska, H., & Marks, R. (2011). 200 years of sea level measurements at the Świnoujście tide gauge – an unique opportunity to study sea level variability at a regional scale. In *Scientific symposium*: *200 years of oldest continuous record of tide-gauge in Świnoujście, 18 November 2011.* Świnoujście, Poland.

Kowalska, B., & Kubicka, A. (2020). Wysokie Poziomy Wody – Zagrożenia Polskiej Strefy Brzegowej w latach 1955-2017. In T. Walczykiewicz (Ed.), *Współczesne Problemy Gospodarki Wodnej w Kontekście Zagospodarowania Przestrzennego* (pp. 57-66). Warszawa: Instytut Meteorologii i Gospodarki Wodnej Państwowy Instytut Badawczy.

Łyszkowicz, A., & Bernatowicz, A. (2018). Geocentric changes of the mean sea level of the Baltic Sea from altimeter and tide gauge data. In *2018 Baltic Geodetic Congress (BGC Geomatics)* (pp. 202-206). IEEE. https://doi.org/10.1109/bgc-geomatics.2018.00044

Łyszkowicz, A., & Bernatowicz, A. (2019). Geocentric Baltic Sea level changes along the southern coastline. *Advances in Space Research*, *64*(9), 1807-1815. https://doi.org/10.1016/j.asr.2019.07.040

Madsen, K. S., Høyer, J. L., Suursaar, Ü., She, J., & Knudsen, P. (2019). Sea level trends and variability of the Baltic Sea from 2D statistical reconstruction and altimetry. *Frontiers in Earth Science*, *7*, 243. https://doi.org/10.3389/feart.2019.00243

Meier, H. E., Kniebusch, M., Dieterich, C., Gröger, M., Zorita, E., Elmgren, R., … & Zhang, W. (2022a). Climate change in the Baltic Sea region: A summary. *Earth System Dynamics*, *13*, 457-593. https://doi.org/10.5194/esd-13-457-2022

Meier, H. E. M., Dieterich, C., Gröger, M., Dutheil, C., Börgel, F.,Safonova, K., … & Kjellström, E. (2022b). Oceanographic regional climate projections for the Baltic Sea until 2100, *Earth System Dynamics*, *13*, 159-199. https://doi.org/10.5194/esd13-159-2022

Meier, H. M., Reckermann, M., Langner, J., Smith, B., & Didenkulova, I. (2023). Overview: The Baltic earth assessment reports (BEAR). *Earth System Dynamics*, *14*(2), 519-531. https://doi.org/10.5194/esd-14-519-2023

Mengel, M., Nauels, A., Rogelj, J., & Schleussner, C. F. (2018). Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. *Nature Communications*, *9*, 601. https://doi.org/10.1038/s41467-018-02985-8

Miętus, M., Filipiak, J., & Owczarek, M. (2004). Klimat wybrzeża południowego Bałtyku. Stan obecny i perspektywy zmian. In: J. Cyberski (Ed.), Środowisko polskiej strefy południowego Bałtyku – stan obecny i przewidywanie zmiany w przededniu integracji europejskiej (pp. 11-44). GTN.

Moberg, A., Tuomenvirta, H., & Nordli, P. Ø. (2005). Recent climatic trends. In M. Seppälä (Ed.), *The Physical Geography of Fennoscandia* (pp. 113-133). The Oxford Regional Environments Series, Oxford University Press.

Musielak, S., Furmańczyk, K., & Bugajny, N. (2017). Factors and Processes Forming the Polish Southern Baltic Sea Coast on Various Temporal and Spatial Scales. In J. Harff, K. Furmańczyk, & H. von Storch (Eds.), *Coastline changes of the Baltic Sea from south to east* (69-85). Cham: Springer. https://doi.org/10.1007/978-3-319-49894-2_5

Nauka o Klimacie. (2021; accessed November 2025). Wprowadzenie do 6 Raportu IPCC. https://naukaoklimacie.pl/aktualnosci/wprowadzenie-do-6-raportu-ipcc-490

Novotny, K., Liebsch, G., Dietrich, R., & Lehmann, A. (2005). Combination of Sea-Level Observations and an Oceanographic Model for Geodetic Applications in the Baltic Sea. In *A Window on the Future of Geodesy* (pp. 195-200). Springer Series of IAG Symposia. Berlin–Heidelberg: Springer. https://doi.org/10.1007/3-540-27432-4_34

Pająk, K., & Błaszczak-Bąk, W. (2019). Baltic sea level changes from satellite altimetry data based on the OptD method. *Acta Geodynamica et Geomaterialia*, *16*, 235-244. https://doi.org/10.13168/agg.2019.0019

Palmer, M. D., Domingues, C. M., Slangen, A. B. A., & Boeira Dias, F. (2021). An ensemble approach to quantify global mean sea-level rise over the 20th century from tide gauge reconstructions. *Environmental Research Letters*, *16*(4), 044043. https://doi.org/10.1088/1748-9326/abdaec

Passaro, M., Müller, F. L., Oelsmann, J., Rautiainen, L., Dettmering, D., Hart-Davis, M. G., … & Benveniste, J. (2021). Absolute Baltic Sea level trends in the satellite altimetry era: A revisit. *Frontiers in Marine Science*, *8*, 647607. https://doi.org/10.3389/fmars.2021.647607

Pugh, D. (2004). *Changing sea levels: Effects of tides, weather and climate*. Cambridge: University Press.

Przygrodzki, P., & Letkiewicz, B. (2015). Charakterystyka wezbrań sztormowych wzdłuż polskiego wybrzeża Morza Bałtyckiego. *Inżynieria Morska i Geotechnika*, *3*, 158-165.

Richter, A., Groh, A., & Dietrich, R. (2012). Geodetic observation of sea-level change and crustal deformation in the Baltic Sea region. *Physics and Chemistry of the Earth*, *Parts A/B/C*, *53*, 43-53. https://doi.org/10.1016/j.pce.2011.04.011

Rotnicki, K., & Borzyszkowska, W. (1999). Przyspieszony wzrost poziomu morza i jego składowe na polskim wybrzeżu Bałtyku w latach 1951-1990. In R. K. Borówka, Z. Młynarczyk, & A. Wojciechowski (Eds.), Ewolucja geosystemów nadmorskich południowego Bałtyku (pp. 141-160). Poznań: Bogucki Wydawnictwo Naukowe.

Rutgersson, A., Kjellström, E., Haapala, J., Stendel, M., Danilovich, I., Drews, M., … & Wasmund, N. (2022). Natural hazards and extreme events in the Baltic Sea region. *Earth System Dynamics*, *13*, 251-301. https://doi.org/10.5194/esd-13-251-2022

Schöne, T., Esselborn, S., Rudenko, S., & Raimondo, J. C. (2010). Radar altimetry derived sea level anomalies – The benefit of new orbits and harmonization. In *System earth via geodetic-geophysical space techniques* (pp. 317-324). Berlin–Heidelberg: Springer. https://doi.org/10.1007/978-3-642-10228-8_25

Suursaar, Ü., & Kullas, T. (2009). Decadal changes in wave climate and sea level regime: the main causes of the recent intensification of coastal geomorphic processes along the coasts of Western Estonia. *WIT Transactions on Ecology and the Environment*, *126*, 105-116. https://doi.org/10.2495/cp090101

Sztobryn, M., Kowalska, B., Stanisławczyk, I., & Krzysztofik, K. (2012). Wezbrania sztormowe – geneza, tendencje i skutki działania w strefie brzegowej Bałtyku. In H. Lorenc (Ed.), *Klęski żywiołowe a bezpieczeństwo wewnętrzne kraju* (pp. 195-217). Warszawa: Instytut Meteorologii i Gospodarki Wodnej Państwowy Instytut Badawczy.

Sztobryn, M., & Stigge, H. J. (Eds.) (2005). *Wezbrania sztormowe wzdłuż południowego Bałtyku (zachodnia i środkowa część)*. Warszawa: Instytut Meteorologii i Gospodarki Wodnej.

Uścinowicz, S. (2003). *Relative sea level changes, glacio-isostatic rebound and shoreline displacement in the southern Baltic*. Warszawa: Państwowy Instytut Geologiczny.

Voosen, P. (2020). Seas are rising faster than ever. *Science*, *370*(6519), 901. https://doi.org/10.1126/science.370.6519.901

WCRP Global Sea Level Budget Group. (2018). Global sea-level budget 1993–present. *Earth System Science Data*, *10*(3), 1551-1590. https://doi.org/10.5194/essd-10-1551-2018

Weisse, R., Dailidiene, I., Hünicke, B., Kahma, K., Madsen, K., Omstedt, A., … & Zorita, E. (2021). Sea level dynamics and coastal erosion in the Baltic Sea region. *Earth System Dynamics Discussions*, *2021*, 1-40. https://doi.org/10.5194/esd-12-871-2021

Wiśniewski, B., & Wolski, T. (2009). *Katalogi wezbrań i obniżeń sztormowych poziomów morza oraz ekstremalne poziomy wód na polskim wybrzeżu.* Szczecin: Wydawnictwo Naukowe Akademii Morskiej.

Wolski, T. (2017). *Czasowa i przestrzenna charakterystyka ekstremalnych poziomów wód Morza Bałtyckiego*. Szczecin: Wydawnictwo Naukowe Uniwersytetu Szczecińskiego.

Wolski, T., Giza, A., & Wiśniewski, B. (2025). Application of the probability of extreme sea levels at selected Baltic Sea tide gauge stations. *Water*, *17*(3), 291. https://doi.org/10.3390/w17030291

Wolski, T., & Wiśniewski, B. (2021). Characteristics and long-term variability of occurrences of storm surges in the Baltic Sea. *Atmosphere*, *12*(12), 1679. https://doi.org/10.3390/atmos12121679

Article first received • 9 March 2026
Article accepted • 15 May 2026