BOREAS An international journal of Quaternary research

Giant saltwater inflow in AD 1951 triggered Baltic Sea hypoxia

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Moros, M., Kotilainen, A. T., Snowball, I., Neumann, T., Perner, K., Meier, H. E. M., Papenmeier, S., Kolling, H., Leipe, T., Sinninghe Damsté, J. S. & Schneider, R. 2024 (April): Giant saltwater inflow in AD 1951 triggered Baltic Sea hypoxia. *Boreas*, Vol. 53, pp. 125–138. https://doi.org/10.1111/bor.12643. ISSN 0300-9483.

A marked sedimentological change in subsurface sediments from the entire Baltic Proper, the Baltic Sea, has been previously noted. Our detailed work on a variety of multi-cores from basin-wide transects indicates that this sedimentological change was caused by a large shift in environmental conditions during the 1950s. Until the 1950s, the water column was rather weakly stratified and winter-time convection – although weakened during the post Little Ice Age warming – was still able to ventilate the bottom waters of the Baltic Proper. Therefore, complete sediment sequences only accumulated in calm waters deeper than 150–160 m. High-resolution benthic foraminiferal records of subsurface sediments obtained along the saline water inflow pathway in combination with historical data indicate that the depositional environment changed drastically owing to the giant saline water inflow in AD 1951. The accompanied sharpening of the halo(pycno)cline triggered a collapse in the ventilation of the basin, resulting in oxygen-deficient bottom waters. This deficiency, in turn, caused the onset of phosphate release from the sediments, which accelerated primary production. The ventilation collapse also enabled the onset of deposition of organic carbon-rich sediments also in shallower water areas as calm conditions prevailed up to the modern winter mixing depth (60–70 m). A slight return to Little Ice Age-type conditions was observed during the late 1980s when temperatures decreased and stratification weakened. These conditions gave rise to a reduction in hypoxic areas and to a bottom-water ventilation, most pronounced in the north of the so-called Baltic Sea Klint, a hydrographic and topographic barrier. However, the general environmental conditions essentially have not changed since the 1950s. Remarkably, external (temperature and stratification) in combination with internal factors (e.g. ventilation collapse and phosphate release) were able to change the redox conditions of the Baltic Proper from oxic to hypoxic within less than 10 years.

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The near-seabed sedimentary record in the Baltic Proper, referred to as the area covering the Eastern and Western Gotland Basin, Fårö Deep, Northern Central Basin and Landsort Deep in the Baltic Sea (Fig. 1) is characterized by a marked sedimentological change. Sediments below this boundary are homogenous, showing high silt and clay but low total organic carbon (TOC) and biogenic silica contents, whereas those closer to the surface are TOC and biogenic silica rich and often laminated (e.g. Fig. 2). This sedimentological change has been linked to an alteration of the redox state of the bottom waters from oxic to hypoxic and even anoxic (e.g. Hille *et al.* 2006; Conley *et al.* 2008; Kabel *et al.* 2012; Jilbert & Slomp 2013; Kotilainen *et al.* 2014; Andrén *et al.* 2020; Moros *et al.* 2020; Kaiser *et al.* 2022). The details of how this change occurred, however, remain largely unknown. The gradual climatic warming after the Little Ice Age (LIA, AD ~1300 to ~1850), evident from atmospheric (Alexandersson & Eriksson 1989; Moberg 2022) and water (e.g. Soskin 1963; Fonselius 1969; Alenius & Haapala 1992; Fonselius & Valderrama 2003; Kniebusch *et al.* 2019; Meier *et al.* 2019; Dutheil *et al.* 2022; Meier 2022) temperature data, may explain the gradual decrease in suspended matter delivery to the deeper basins owing to a weakening of the winter-time ventilation (Moros *et al.* 2020). However, the sudden stop of re-suspended matter delivery to the sub-basins and the abrupt onset of widespread TOC accumulation in shallower water areas on top of over 10 000-year-old Baltic Ice Lake sediments (Moros *et al.* 2020) cannot be explained only by the gradual climate warming.

A changing degree of water column stratification of the Baltic Sea has been proposed as a potential mechanism for a sudden environmental change (Fonselius 1969). In the Baltic Sea, outflowing brackish water at the surface and inflowing saltier and, hence, denser water from the North Sea close to the seafloor establish a pronounced pycnocline. Given the recent regional hydrographic and climatic conditions, oxygenation of the deep parts of the central sub-basins is only possible by lateral inflows of dense, oxic waters which can penetrate below the pycnocline.

DOI 10.1111/bor.12643

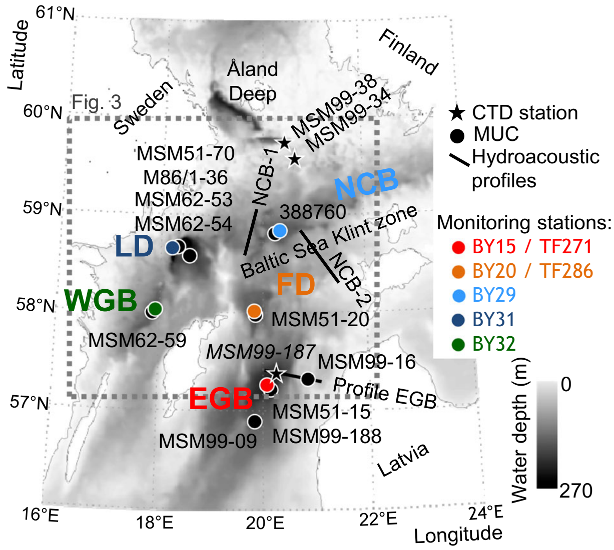

Fig. 1. Bathymetric map showing the various sub-basins (WGB = Western Gotland Basin; EGB = Eastern Gotland Basin; FD = Fårö Deep; NCB = Northern Central Basin; LD = Landsort Deep) of the Baltic Proper and key multi-core (black dots), CTD (asterisk) and hydrographic monitoring (coloured dots) stations. Black bold lines indicate locations of hydroacoustic profiles and the box marked with a dashed grey line displays the map area shown in Fig. 3. The topographic barrier named 'Baltic Sea Klint' is indicated. Locations of additional multi-cores are not shown in this figure but are revealed in the respective hydroacoustic profiles (Figs 4, S3–S5).

Hydrographic and environmental changes associated with such inflows have been extensively studied over the last two decades (Meier *et al.* 2006; Matthäus *et al.* 2008; Neumann *et al.* 2017; Mohrholz 2018; Liblik & Lips 2019; Radtke *et al.* 2020; Meier 2022). Effective oxygenation of the central Baltic Sea requires strong inflow events, so-called major baltic inflows (MBI) (Matthäus & Franck 1992; Fischer & Matthäus 1996). The largest recorded inflow with the highest salinity in the whole period of instrumental measurements occurred in AD 1951 (Mohrholz 2018). However, during colder periods (Moros *et al.* 2020) and also in the early 20th century it is assumed that winter-time convection (e.g. Granqvist 1938; Fonselius 1969) is also a key process that ventilates the bottom waters of the Baltic Sea. Sediment proxy studies focussed on water-mass changes using geochemical measurements (e.g. Kunzendorf & Larsen 2009; Jilbert & Slomp 2013; Lenz *et al.* 2015; Häusler *et al.* 2018; Dellwig *et al.* 2021). They detected changes, which are mainly related to redox conditions and not to salinity, in the Baltic bottom water mass over the instrumental data period, the period since the early 1960s. The presence of distinct manganese–carbonate layers in the sediments of the Eastern Gotland Basin has been shown to result from MBIs (e.g. Neumann *et al.* 1997, 2002; Moros *et al.* 2017). The potential of the study of benthic foraminifera as a proxy for bottom-water salinity was already demonstrated by Lutze (1965), who studied the effect of MBIs on the distribution of benthic foraminifera in the Belt and Baltic Sea during the early 1960s.

The accuracy and precision of the geochronological control for central Baltic Sea basin sediment sequences that cover the last decades – critical to establishing a link to instrumental data – have been significantly improved (Moros *et al.* 2017; Häusler *et al.* 2018; Kaiser *et al.* 2022). Instrumental hydrographic data are available from AD 1890 but at a rather low temporal and spatial resolution until the late 1950s. However, from the 1960s onwards the resolution of these observations increased markedly, both temporarily and spatially (Meier 2022).

Here we study the marked sedimentary boundary in subsurface sediments from a variety of sites in the Baltic Proper, in both shallow and deep water. The sites were selected based on hydroacoustic profiling results. Water column stratification changes – possibly linked to the marked sedimentary boundary – will be reconstructed by obtaining benthic foraminiferal records in high resolution. Well-constrained age models will allow the sedimentary change to be related to historical hydrographic data.

Materials and methods

Short sediment cores (Fig. 1, Table S1) were collected using a multi-corer equipped with 60-cm-long tubes during cruises with RV 'Prof. Albrecht Penck' in 2009, and RV 'Maria S. Merian' in 2016 (MSM51), 2017 (MSM62) and 2021 (MSM99). Surface sediments were recovered with a multi-corer during RV 'Elisabeth Mann Borgese' cruises (EMB-95 and EMB-100) in February and April 2015 shortly after the MBI in 2014. Hydrographic conductivity, temperature, depth (CTD) measurements at two sites and three hydroacoustic PARASOUND profiles were obtained during the RV 'Maria S. Merian' MSM99 expedition in 2021 (Fig. 1, Table S1). The sediment cores were cut lengthwise on board or in the laboratory prior to photography, macroscopic sediment description, X-ray fluorescence (XRF) scanning and discrete contiguous subsampling.

Sediment analyses

Identification of age–depth control points in multi-cores. – The identification of age–depth control points in central Baltic Sea subsurface sediments follows the event stratigraphic approach described by Moros *et al.* (2017). For this research, the identification of the stratigraphic position of the Chernobyl nuclear power plant accident in 1986 is crucial and straightforward. AD 1986 is evident as a sharp ^{137}Cs increase in published and newly obtained records (Table S1). Additional isochrons have been identified according to Moros *et al.* (2017), i.e. the Hg pollution maximum of the 1960s–1970s, a broad ^{241}Am spike marking the nuclear weapons test phase from 1951 to 1975 (with the peak in 1963) and manganese-carbonate layers of the MBIs in AD 1993

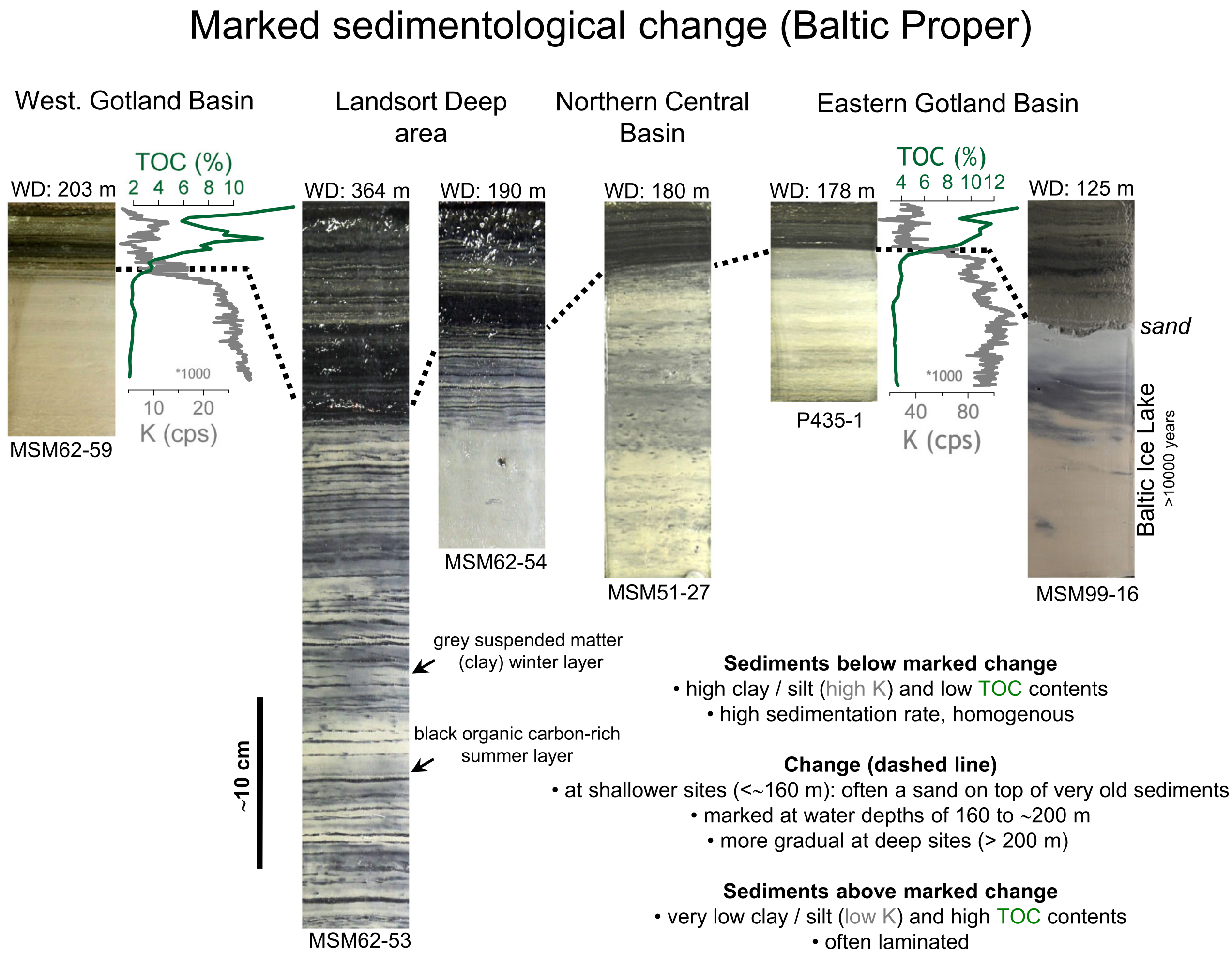

Fig. 2. Photographs of subsurface sediment cores (cut in half) taken at different water depths displaying the marked sedimentological change (bold dashed black line) observed in sub-basins of the Baltic Proper. Typical features of the sediments above and below the change are presented also with regard to the water depth of the respective coring site. The total organic carbon (TOC) content and potassium (K in counts per second) X-ray fluorescence (XRF) scanner data of two cores are additionally shown.

and 2003. The shape of the downcore profiles and the successive order of the individual time markers are proof of continuously deposited sediments free from post-depositional mixing. Artificial radionuclide (^{137}Cs, ^{241}Am) and mercury (Hg) measurements were carried out at the Leibniz-Institute for Baltic Sea Research Warnemünde (IOW) following the methods described by Moros *et al.* (2017). New radionuclide measurements were obtained on MSM15-15, -20, -70, MSM62-54 and MSM99 multi-cores. M81/1-36 and MSM62-59 data are published in Häusler *et al.* (2018) and Andrén *et al.* (2020), respectively, and the time marker positions from core 377860 and part of core MSM51-15 were published in Moros *et al.* (2017).

Total organic carbon content. – The total carbon (TC) and the total inorganic carbon (TIC) contents were measured using an EA 1110 CHN analyser (CE Instruments) and a Multi EA-2000 Elemental Analyser (Analytic Jena), respectively. The TOC content was calculated as the difference between TC and TIC.

XRF scanning of cores. – The Mn–Ca layers were identified by XRF scanning. Split core surfaces were carefully prepared using a scraper. Manganese and potassium (K) distribution were determined with ITRAX XRF core scanners (COX Analytical, Croudace *et al.* 2006) at a stratigraphic resolution of typically 300 μm at IOW and the University of Cologne. X-ray absorbance (a proxy for sediment density) was also obtained as grey-scale images at approximately the same resolution. A chrome (Cr) tube operating at 30 kV and 30 mA with an exposure time of 15 s per step was employed for the elemental scan, but at 60 kV and 25 mA with a typical exposure time of between 400 and 700 ms for X-ray scanning.

Benthic foraminifera. – Sediment horizons of mostly 1 cm (M86/1-36 at 0.5 cm) from 11 multi-cores were gently wet sieved at 63 µm and the foraminifera counted wet under a stereo microscope. The number of benthic foraminifera were expressed per gram of sediment. Subsamples for benthic foraminifer counting were taken immediately after core recovery or shortly after cruise termination (M86/1-36) to minimize the problem of test dissolution (Wefer & Lutze 1978; Binczewska *et al*. 2018).

Hydrographic instrumental monitoring data

Instrumental time series (AD 1950–2021) data for near-bottom-water hydrographic parameters (oxygen, salinity, temperature) from the basins studied were downloaded from the Swedish Ocean Data Archive (SHARK, http://sharkweb.smhi.se) of the Swedish Meteorological and Hydrological Institute (Sweden) (Fig. 1, Table S1). Monitoring stations BY15 (Eastern Gotland Basin), BY20 (Fårö Deep), BY29 (Northern Central Basin), BY31 (Landsort Deep) and BY32 (Western Gotland Basin) were used. The salinity data of the Bornholm Basin (85–90 m) are from Mohrholz (2018).

Results

Sedimentology

All sediment cores obtained showed the marked sedimentary boundary (e.g. Fig. 2). At the boundary the silt and clay disappear, and the TOC content increases strongly upwards in the sediment column. In the deeper sub-basins of the Baltic Proper (>200 m water depth) this sedimentological change appears more gradual (Fig. 2; see also Moros *et al*. 2020). However, at sites with a water depth of between 200 and approximately 150 m, the sedimentary boundary is sharp. Moreover, at sites with water depths <150 m TOC-rich laminated mud is often found on top of a sandy layer (Fig. 2). Below the sand layer typically varved reddish/brownish to grey clayey sediments of the Baltic Ice Lake stage older than 10 000 years are found. Close to the contact with the overlaying TOC-rich mud the formerly reddish/brown clays are often diagenetically bleached (e.g. Moros *et al*. 2002). It has been shown previously that the silty and clayey material that accumulated below the sedimentary boundary is composed of *in-situ* produced as well as re-deposited matter that was re-worked during the cold LIA, most likely by winter-time convective processes (Moros *et al*. 2020).

Geochemistry

The marked sedimentological change that is macroscopically clearly visible in all multi-cores from the basins of the entire Baltic Proper (Fig. 3A–E) is distinctly traced by profiles of K counts using XRF scanning. At the sedimentary boundary, they reveal a marked drop or near disappearance in many cores in the content of silty and clayey material content rich in potassium (Fig. 2). At the same time, the TOC content rapidly increases (Fig. 2). X-ray fluorescence scanning of Mn reveals the presence of distinct manganese-carbonate layers in the sediment cores from locations south of the Baltic Sea Klint (Figs 3A, S1). These layers can be related to the MBIs in AD 1993, 2003 and 2014 (e.g. Moros *et al*. 2017). The robust stratigraphic markers of AD 1986 (Chernobyl accident), revealed by the maximum in the ^{137}Cs record, and of AD 1963, revealed by the maximum in the broad ^{241}Am spike marking the nuclear weapons test phase from AD 1951 to 1975, were identified in all cores (Figs 3, S1, S2). These age assignments are consistent with the Hg pollution maximum of the 1960–1970s (Figs 3, S1, S2). Based on these isochrons, the timing of the marked sedimentological change is well before AD 1963 but after the start of the nuclear weapons testing (Figs 3, S1, S2). In combination with other detailed chronological analyses (Moros *et al*. 2017; Kaiser *et al*. 2022), our analyses indicate that the marked sedimentological change occurred nearly simultaneously in all sub-basins during the mid to late 1950s (most likely AD 1955–1958).

Benthic foraminifera

In general, the benthic foraminiferal assemblages analysed are dominated by calcareous tests of the genus *Elphidium* and a few arenaceous *Reophax dentaliniformis*, which agrees with earlier down-core studies by Brodniewicz (1965), Hermelin (1987), Kotilainen *et al*. (2014), Häusler *et al*. (2017), Binczewska *et al*. (2018), Van Wirdum *et al*. (2019) and Ponomarenko and Krechik (2018). In addition, Lutze (1965) reported *Elphidium excavatum f. clavatum* (defined as *Cribrononion excavatum f. clavatum*) in surface sediments as the dominant taxon inhabiting the Gotland Basin during the AD 1962–1964 saline water inflows. In the surface (0–1 cm) sediments obtained in AD 2015 (Table S1), these benthic foraminifera were present at site TF271 (Eastern Gotland Basin), but were absent at site TF286 (Fårö Deep; see Fig. 1 for locations). The depth profiles of the benthic foraminiferal abundance from a transect along the saline water inflow pathway are shown in Fig. 3. Most striking is the numerically massive benthic foraminifera occurrence with thousands of tests per gram of sediment in the uppermost part of the silty clayey homogenous sediments just below the marked sedimentological change in all sub-basins of the Baltic Proper (dashed horizontal line in Figs 3A–E, S1, S2). In the Landsort Deep this benthic foraminiferal spike is detected up to a water depth of 110 m. South of the Baltic Sea Klint benthic foraminifera are found in low numbers in the manganese carbonate layer representing the MBI in AD 1993 and in higher numbers in the AD 2003 and 2014 layers in the Eastern Gotland Basin (Fig. 3A; note that

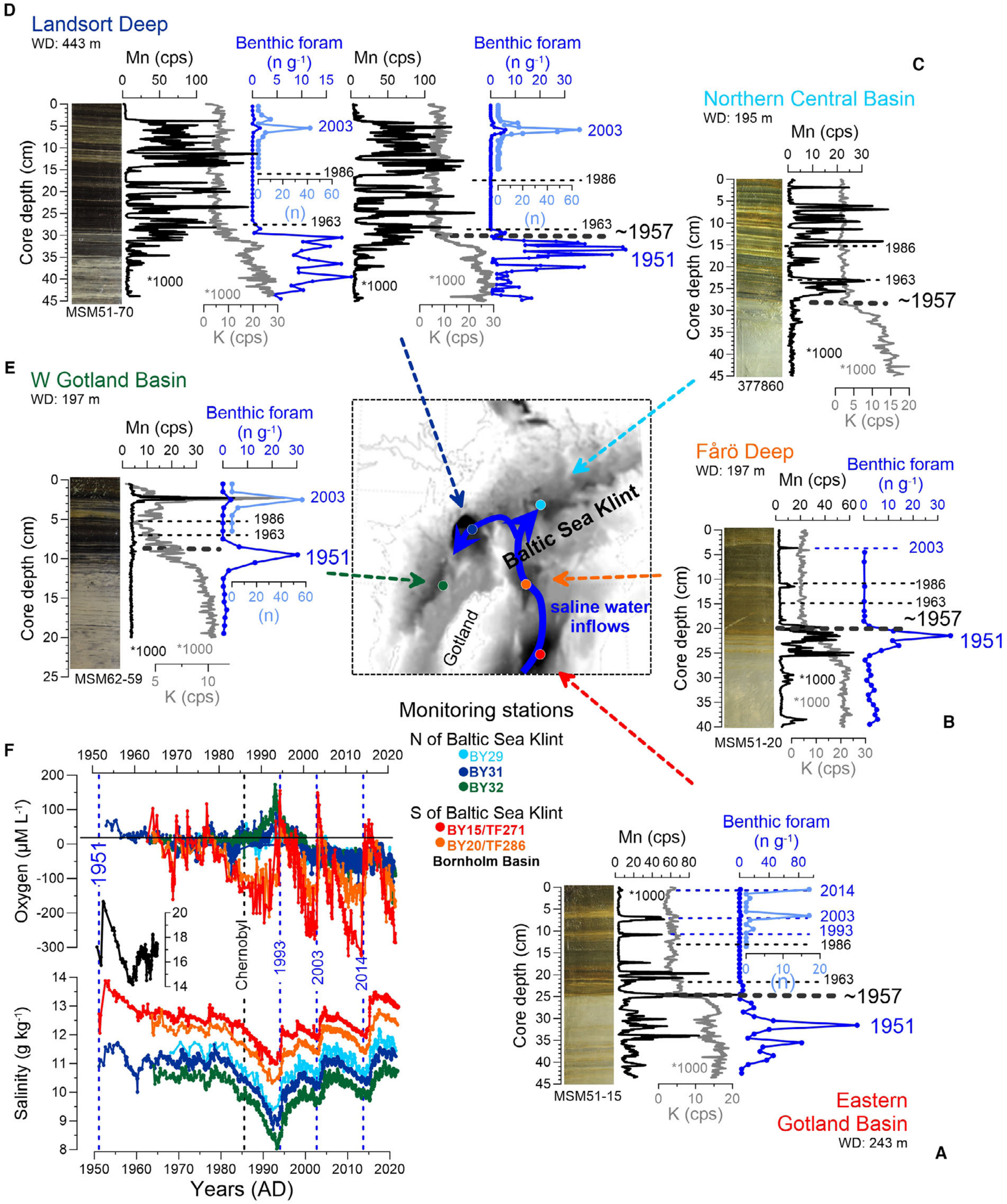

Fig. 3. Multi-corer photos, XRF data (Mn, K in counts per second) from sites/sub-basins located around the island Gotland (A–E) along the paths of saline water inflows from the North Sea. Monitoring data shown (F) are from the same sub-basins (plus Bornholm Basin in black). The time markers AD 1986 Chernobyl and AD 1963 bomb test maximum are indicated in all records. Manganese-carbonate layers are reflected as Mn spikes in the XRF elemental data. Blue numbers in A–E mark the respective identified major baltic inflow (MBI) layers based on the benthic foraminiferal counts (test numbers for the MBIs 1993, 2003 and 2014 are zoomed in light blue). Benthic foraminifera are found south of the Baltic Sea Klint in all MBI layers (A). However, north of the Klint only one spike appears after AD 1986 (D and E), which is linked to the MBI 2003. Horizontal dashed bold lines indicate the marked sedimentological change in A–E. The change occurred shortly after the giant saline water inflow in 1951. Note the different sediment proxy record features north (marked manganese-carbonate formations in C and D) and south (manganese-carbonate formation only as a result of saline water inflow from the west in A and B) of the Baltic Sea Klint for the time of the late 1980s. Simultaneously, the near-bottom waters of northern sub-basins became oxic whereas in the southern sub-basins anoxic conditions prevailed (F).

for these MBI layers the number of counted foraminifera tests is shown separately in light blue). In all sub-basins north of the Baltic Sea Klint (Northern Central Basin, Landsort Deep, Western Gotland Basin), there is only one benthic foraminiferal peak and with a rather high number of tests (Fig. 3D, E in light blue) in sediments accumulated since AD 1986 linked to a manganese-carbonate layer (Figs 3D, E, S1). This layer containing benthic foraminifera is present near the top of a thick unit of manganese-carbonate layers in sediments deposited shortly after AD 1986 and those manganese-carbonate layers do not contain foraminifera. Based on a combination of the observations from east of Gotland, upstream of the inflow path, and the instrumental time series data, it is evident that the upper foraminiferal layer marks the MBI 2003 (Figs 3D, E, S1).

Discussion

The marked sedimentological change in cores along transects

To discover the reason why and when the delivery of fine-grained silty–clayey sediment to the central basins stopped and the accumulation of TOC-rich material started in shallower water areas, an examination of the sedimentological change in multi-cores along transects from deep to shallower waters is essential. Three selected transects, one from the Eastern Gotland Basin (Fig. 4) and two from the Northern Central Basin (Figs S3, S4) obtained during winter cruise MSM99 were examined. Continuous sediment sequences from the LIA period towards the present day are found only in sediments at

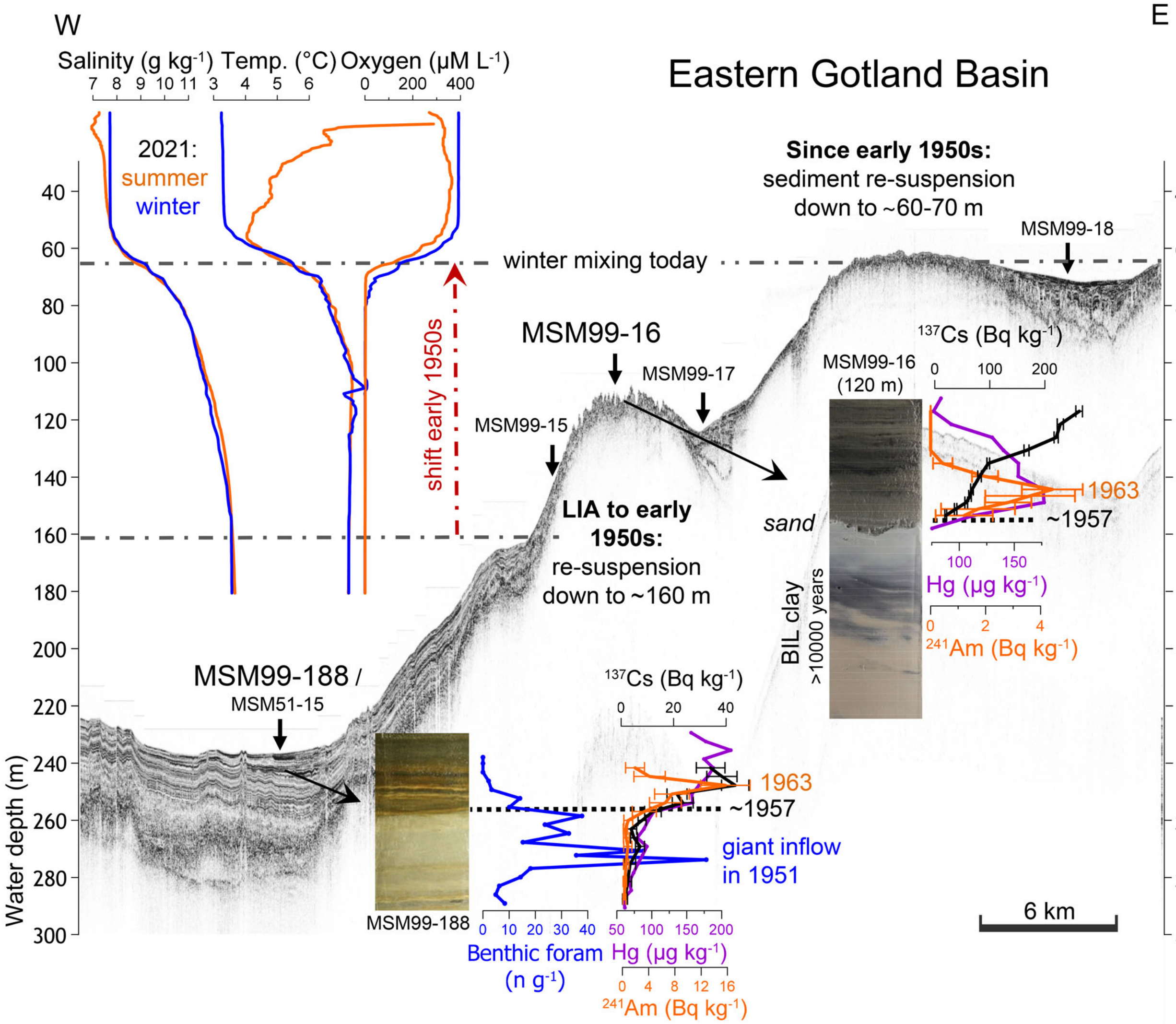

Fig. 4. Hydroacoustic PARASOUND profile from the Eastern Gotland Basin. Subsurface sediment cores were taken on a depths transect from ~240 to 80 m. Stratigraphic markers from two sites bathed at 237 m (MSM99-188 plus benthic foraminiferal counts) and 120 m (MSM99-16) water depth, respectively, are shown. Note that the environmental and sedimentological (dashed horizontal line ~1957) change occurred shortly after the giant saline inflow in 1951 (numerically massive appearance of benthic foraminifera). Since the mid-1950s calmer conditions have enabled the accumulation of organic-carbon-rich material also in shallower areas up to the modern winter-time mixing depth of 60–70 m (see summer and winter CTD data upper left). Time marker: AD 1963 nuclear weapons test maximum.

water depths greater than ~150–160 m in all sub-basins (Figs 4, S3, S4). At shallower sites only very young TOC-rich sediments are found directly on top of much older sediments, clays deposited during the Baltic Ice Lake phase of the Baltic Seas history, >10 000 years ago (i.e. Fig. 4: site MSM99-16; Fig. S3: sites MSM99-21 and -23; Fig. S4: sites MSM99-27, -28 and -29). This indicates a hiatus of up to several thousand years. Often a sandy layer is observed separating the laminated mud unit from the Baltic Ice Lake clays. The sand layer probably formed as a result of stronger bottom currents which gave rise to winnowing of older sediments probably during the LIA (cf. Moros *et al.* 2020). Age control reveals that TOC-rich mud deposition did not occur in the shallower water areas between 150 and 60–70 m before the 1950s (Figs 4, S3, S4). Evidently, calm sediment settling conditions did not occur during that time. As the Eastern Gotland Basin transect exemplifies (Fig. 4), the marked sedimentological change in the mid to late 1950s happened shortly after the giant inflow AD 1951 (Fig. 4, MSM99-188). At approximately the same time sediment deposition in shallower water areas (Fig. 4, MSM99-16) up to the modern winter-time mixing depth at 60–70 m set in. It is noteworthy that also in other basins, like the Bornholm Basin (exemplified in Fig. S5), the accumulation of laminated TOC-rich mud on top of old Baltic Ice Lake clay started at the respective sites (i.e. >60–70 m but <150–160 m) after the saline water inflow AD 1951.

Presently fine-grained sediments are not found at water depths <60–70 m in the Baltic Proper, which marks the modern winter-time mixing and halo(pycno)cline depth (Fig. 4, CTD data). Organic carbon formed in surface waters by primary production during summer, which accumulated in areas at <60–70 m water depth as a fluffy layer, is most likely re-worked and re-deposited in deeper areas by the winter-time mixing. This caused a high sediment accumulation in rather shallow coastal small basins since the mid-to late 1950s (e.g. Fig. 4: sites MSM99-17 and -18, see Fig. S2 for time markers).

Benthic foraminifera as indicators of past saline water inflows

Instrumental data indicate that during phases characterized by strong saline water inflows the hydrographic conditions are similar in the entire Baltic Proper (e.g. Fig. 3F; Fonselius & Valderrama 2003). During periods characterized by no or only weak saline inflows, hydrographic data and sedimentary records indicate that the bottom-water oxygen development (Fonselius & Valderrama 2003) and the formation of manganese-carbonate layers (e.g. Lenz *et al.* 2015; Moros *et al.* 2017; Häusler *et al.* 2018) are different in the sub-basins north and south of the marked topographic feature known as the Baltic Sea Klint (Figs 1, 3; Tuuling & Flodén 2016). The Klint's importance as a hydrographic barrier during the past has been discussed in detail by Moros *et al.* (2020).

Our results confirm Lutze's (1965) observation that two major hydrographic pre-conditions must be met before populations of benthic foraminifera appear: (i) the presence of oxic bottom waters with (ii) a salinity >~10–11 g kg^{-1}. Thus, for example, in surface sediments taken shortly after the MBI 2014 test of the benthic foraminifer, *E. excavatum* were detected in the Eastern Gotland Basin, but not in the Fårö Deep, even though the salinity exceeded the critical salinity threshold at site TF286. Oxygen deficiency in the Fårö Deep and in all other sub-basins to the north prevented the colonization of benthic foraminifera during the MBI 2014. In line with the instrumental data, this shows that an effective bottom-water ventilation via the AD 2014 inflow occurred only temporarily and was restricted to the Gotland Basin (Neumann *et al.* 2017). During the MBI 2003, however, all sub-basins of the entire Baltic proper were temporarily ventilated, and the salinity increased to >11 g kg^{-1} (Fig. 3F) and, therefore, benthic foraminifera were able to colonize the seafloor. The bottom-water ventilation north of the Baltic Sea Klint during the late 1980s seen in instrumental data and the pronounced formation of manganese-carbonate was, however, not caused by saline water inflows (Fig. 3A–C, F). This bottom-water oxygenation-ventilation event, which did not occur in the sub-basins south of the Baltic Sea Klint, must have been triggered by another process. The rather low salinity in the sub-basins north of the Baltic Sea Klint prevented the colonization by benthic foraminifera during MBI AD 1993 even though the area was well ventilated (Fig. 3F).

The stratigraphic framework (e.g., first appearance of ^{241}Am and ^{137}Cs) and comparison with hydrographic measurements (Figs 3F, S1, S2) provide strong evidence that the numerically massive occurrence of benthic foraminifera with thousands of tests per gram of sediment in the uppermost part of the silty clayey homogenous sediments just below the marked sedimentological change in all sub-basins of the Baltic Proper formed as result of the saline water inflow AD 1951. This giant inflow (i.e. the largest recorded inflow with the highest salinity in the whole period of instrumental measurements; Mohrholz 2018) occurred during a time when the sub-basins of the entire Baltic Proper were ventilated (e.g. Soskin 1963; Fonselius 1969; Fonselius & Valderrama 2003). These unique conditions gave rise to an enhanced bloom of benthic foraminifera in the entire Baltic Proper.

The saline water inflow AD 1951 was the cause of the marked sedimentological, hydrographic and environmental change

The giant inflow of saline water in AD 1951 has been discussed in several publications to be of crucial importance for the hydrographic conditions in the central Baltic Sea (Soskin 1963; Fonselius 1969; Meier *et al.* 2006). Historical instrumental data (Soskin 1963; Fig. 5) and our benthic foraminifera records (Fig. S1:

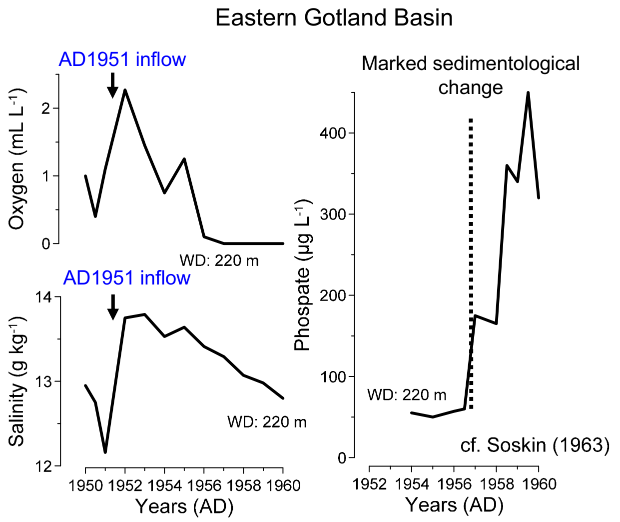

Fig. 5. Valuable Eastern Gotland Basin oxygen, salinity and phosphate data at a water depth of 220 m from the 1950s (modified after Soskin 1963) that show convincingly the effect of the AD 1951 saline water inflow. This dataset is unfortunately not available in known databases. The approximate timing of the marked sedimentological change is indicated with a vertical dashed black line.

MSM99-09; Kotilainen *et al.* 2014) indicate that the AD 1951 inflow was the culmination of a longer-term trend of increasing salinity, characterized by several inflow pulses. As a result of this inflow the difference in density between the surface and the deep water (i.e. the halocline; see Sverdrup *et al.* 1942) increased and resulted in the highest stability of the halocline (Fig. S6E; cf. Fonselius 1969), leading to a significant weakening of vertical convection, which established calm settling conditions, a prerequisite for the onset of sediment accumulation also in shallower water areas up to 60–70 m. Our records from the multi-core transects clearly indicate that at this time the water depths to which sediment re-suspension occurred shifted from ~150 to 160 m (LIA to the 1950s) to 60–70 m, i.e. the modern winter mixing depth (Fig. 4).

The initial oxygenated state of the bottom waters of the Gotland Basin, resulting from the AD 1951 inflow, however, quickly altered (Fig. 5; Soskin 1963). The collapse of vertical convection (Fig. S7B; Fonselius 1969) resulting from the increase in stratification led to an oxygen deficit in the bottom waters (Figs 5, S7A–C). This triggered, owing to the very low pH of porewaters, a sudden release of phosphate from the sediments at ~AD 1957/1958 (Fig. 5, cf. Soskin 1963; Fig. S6D, cf. Fonselius 1969; Fonselius & Valderrama 2003). Sediments are by far the main contributor of phosphate to the system (Soskin 1963; Fonselius 1967; Vahtera *et al.* 2007; Stigebrandt & Andersson 2020). The sudden phosphate release accelerated the primary production and led to a marked spread of hypoxia or anoxia in the 1950s, together accounting for increased TOC deposition. The phosphate of the deepwater reaches the surface layer by erosion of the halocline only during autumn and winter when the seasonal summer stratification (thermocline) breaks down and vertical convection reaches down to the halocline (Fonselius 1967; Stigebrandt 1985). This situation actually happens twice per year, i.e. when the winter is (i) approaching and (ii) fading, and the surface water reaches its highest density. Upwelling may also lead to a phosphate increase in surface waters (Eilola *et al.* 2014).

Phosphorus is the most significant growth-limiting nutrient for N_2-fixing cyanobacteria in the Baltic Sea (Stal *et al.* 1999). Prior to the summer bloom of cyanobacteria, the yearly spring bloom of diatoms removes most dissolved inorganic nitrogen and orthophosphate from the surface water. N_2 fixation by a Baltic Sea cyanobacterial community has been shown to be highly sensitive to phosphate availability; a single pulse of phosphate enhanced total biovolume and growth (Olofsson *et al.* 2016). Summer temperatures >16 °C (Kononen 1992; Wasmund 1997) required for cyanobacteria to bloom already occurred early in the 20th century, i.e. well before the 1950s (e.g. Kabel *et al.* 2012). The generally increased primary productivity owing to phosphate release from the bottom sediments together with no influx of re-worked silty clayey material explains the high TOC in the sediments accumulated in the entire Baltic Proper after the 1950s.

The ventilation collapse caused by the giant inflow AD 1951 was decisive. We suggest that the winter-time ventilation/convection had already weakened during the early 20th century when the atmosphere (Alexandersson & Eriksson 1989; Moberg 2022) and the water column of the Baltic Sea (e.g. Soskin 1963; Alenius & Haapala 1992; Fonselius & Valderrama 2003) warmed. In addition, the salinity, and hence stratification, already increased on a longer timescale as a result of smaller inflow pulses. The initial weakening of the winter-time convection before the inflow AD 1951 is seen in sediments of the deepest basins, e.g. in the Landsort Deep (Fig. 1; Moros *et al.* 2020). The giant inflow AD 1951 via a marked stratification increase (Fig. S6E; Fonselius 1969), however, then gave rise to the collapse of the deep-reaching winter-time convection. It is noteworthy that, also in other shallower basins like the Bornholm Basin (Fig. S5), Gulf of Finland and Gdańsk Bay, continuous sediment accumulation started in the 1950s after vertical convection ceased.

The late 1980s: restricted bottom-water ventilation in the sub-basins north of the Baltic Sea Klint

The late 1980s were relatively cold; low temperatures (Alexandersson & Eriksson 1989; Moberg 2022) prevented the occurrence of cyanobacterial blooms during summer (Kahru *et al.* 1994; Kabel *et al.* 2012), and gave rise to a strong sea-ice formation phase (Haapala *et al.* 2015). A parallel increased vertical convection caused a much higher N/P ratio in the surface layer (Stigebrandt & Andersson 2020) and increased diatom blooms in nearly all sub-basins (Wasmund *et al.* 2004; Moros *et al.* 2017). In particular, the stratification in the sub-basins north of the Baltic Sea Klint weakened markedly during a phase of weak saline water inflows (Fig. 6, so-called stagnation period; see Meier *et al.* 2006). North of the Baltic Sea Klint – and only there – the weakened stratification together with colder air temperatures enabled ventilation of bottom waters, which is clearly not caused by saline water inflows (Figs 3F, 6). This deep-water ventilation is evident from instrumental time series data (Fig. 6) and the marked formation of manganese carbonate layers in sediments accumulated after the Chernobyl accident AD 1986 in the northern sub-basins (Fig. 3B, C). Enhanced sediment re-suspension and lateral influx is recorded in sediment cores taken in marginal shallower parts of the Landsort Deep and the Western Gotland Basin, but not in the deep basins. In addition, in the Eastern Gotland Basin the halocline deepened, larger bottom areas were ventilated and the hypoxic area declined by a factor of 3–4 (Krapf *et al.* 2022). However, there was no bottom-water ventilation in the deep sub-basin (Fig. 3F).

In addition to increased vertical convection through a weakened halocline there are clear indications of lateral oxygenated water influx from northern sources. The inflow channel(s) can be traced by detailed mapping of manganese-carbonate layer occurrence in multi-cores taken on north–south transects north of the Baltic Sea Klint (Fig. S4). The Klint with its 100 m sill depth prevented the inflow of dense oxygenated bottom water to the southern sub-basins and formed again a hydrographic barrier (Moros *et al.* 2020). The ventilation during the cold late 1980s led to a shrinking of the hypoxic area in the central Baltic Sea (Carstensen *et al.* 2014; Fig. S6C, cf. Stigebrandt & Andersson 2020). The late 1980s conditions resemble – but to a much lesser extent – the LIA conditions. Owing to the rather

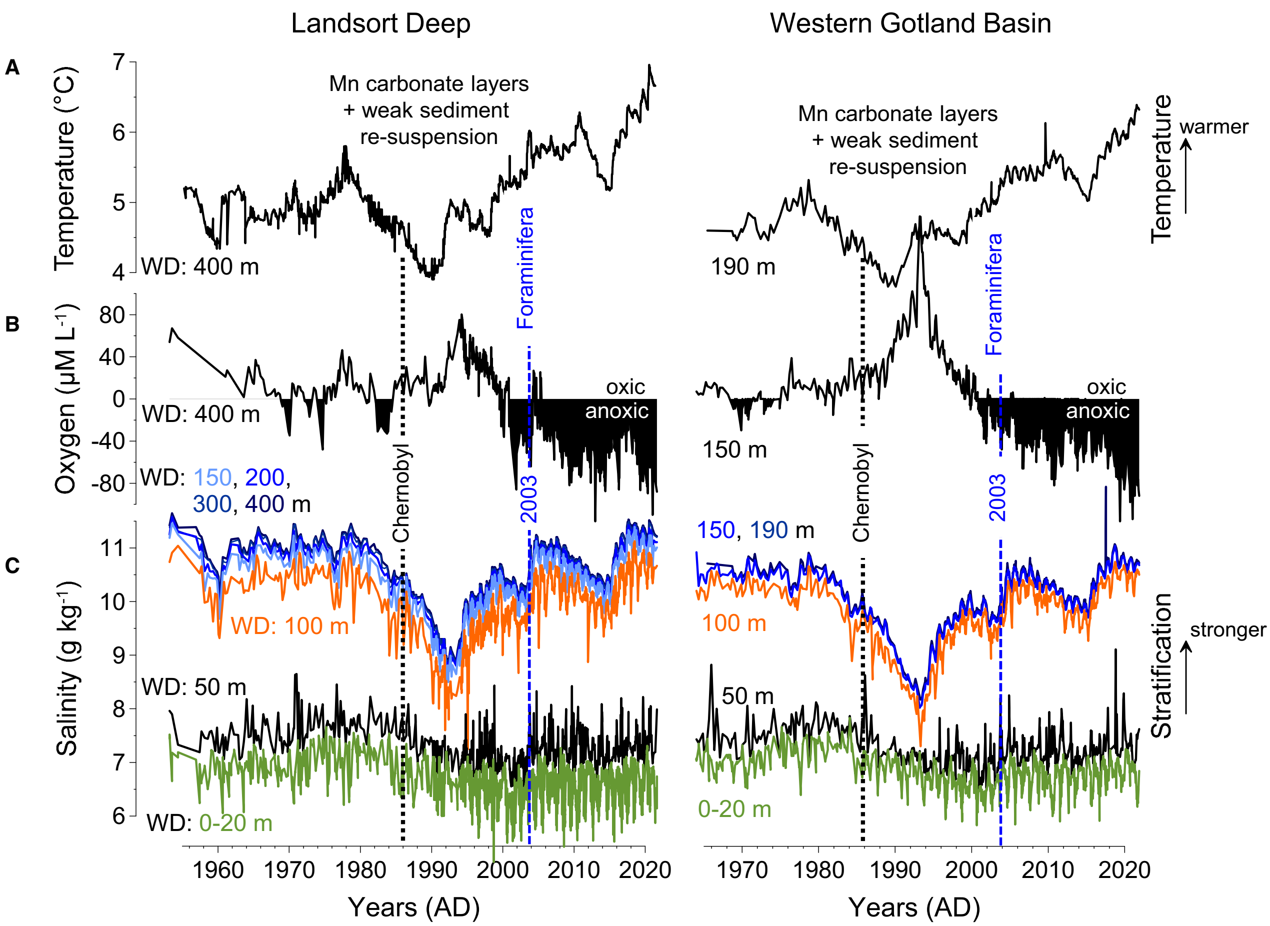

Fig. 6. Hydrographic monitoring data from the Landsort Deep (BY31) and the Western Gotland Basin (BY32), sites located north of the Baltic Sea Klint. Temperature (A) and oxygen (B) data are from the deep-water layer. Salinity data (C) from different water depths (WD) emphasize the marked stratification change (stagnation) during the late 1980s. During this phase of weak stratification (C) and cold air and water (A) temperatures a bottom-water oxygenation (B) occurred without saline water inflow influence (manganese-carbonate layers in sediments but no benthic foraminifers). Slight ventilation during the MBI AD 2003 is seen in monitoring (B) and sediment proxy data (e.g. Fig. 3).

moderate temperature decrease the improvement of bottom-water conditions of the deepest sub-basin parts remained restricted to the sub-basins north of the Baltic Sea Klint during the late 1980s. Since the early 1990s atmospheric temperature has increased. The saline water inflows of AD 1993 and 2003 increased the salinity of the bottom waters, and hence strengthened stratification. Hypoxic and anoxic conditions prevailed except during a short oxygenation event linked to the MBI 2003 when the basins north of the Baltic Sea Klint were also ventilated (Figs 3F, 6). In the late 1980s the Baltic Sea Klint formed the border between anoxic (south) and oxic (north) bottom waters (Fig. 3F). In winter 2021 the boundary between oxic and anoxic bottom waters was located at a sill SE of Åland Deep (Fig. S3, between stations MSM99-34 and MSM99-38).

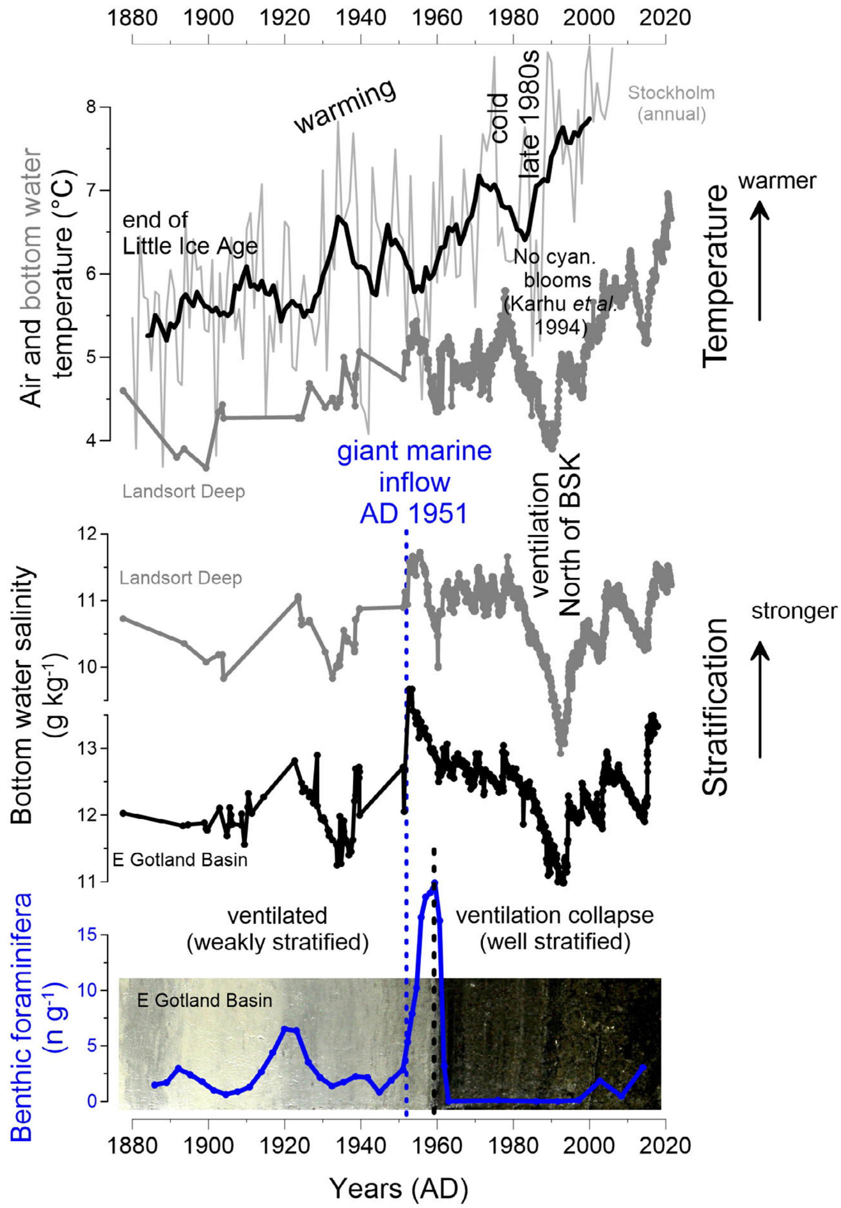

Fig. 7. Long-term warming trend from the end of the Little Ice Age towards the present day is seen in air (Stockholm; Moberg 2022) and bottom-water (Landsort Deep BY31) temperature data (A). Bottom-water salinity data from Landsort Deep (BY31) and Eastern Gotland Basin (BY15) shown in B agree well with sediment proxy benthic foraminiferal counting data (C, MSM99-09 from southern Eastern Gotland Basin). The marked sedimentological change (photograph shown in C, vertical dashed black line) occurred after the giant saline water inflow in AD 1951 (vertical dashed blue line) as vertical ventilation through the halocline collapsed. Since the 1950s the general depositional environment essentially has not changed. Colder temperatures in the late 1980s (A) and a parallel weakened stratification (B and C) enabled a ventilation north of the Baltic Sea Klint (BSK).

Conclusions

The marked sedimentological change seen in sub-recent seabed sediment cores from the entire Baltic Proper can be attributed to large hydrographic and environmental changes that started at the end of the LIA and were accelerated by a rapid change in stratification resulting from the giant saline water inflow in AD 1951. On a longer timescale, winter-time deep-water convection gradually weakened owing to the warming of the atmosphere and ocean after the end of the LIA but still contributed to complete ventilation of bottom waters of the entire Baltic Proper, while currents prevented accumulation and even eroded sediments above a water depth of approximately 150–160 m until the early 1950s (Fig. 7). The gradually decreasing intensity of ventilation of bottom waters is suggested based on records obtained from the deepest basins. The hydrographic conditions changed markedly with the giant saline water inflow AD 1951. The accompanied increase in stratification caused a collapse of the already weakened vertical convection, leading to hypoxia in the bottom waters (Fig. S7C), which in turn forced a sudden phosphate release from the sediments (Fig. 5) and increased primary production in the late 1950s. The sharp sedimentological boundary reflects this sudden environmental change: with the convection collapse the delivery of fine-grained re-worked material to the sub-basins stopped, the base of sediment re-suspension shifted upwards and much calmer conditions prevailed also in shallower water areas until today. This enabled from the late 1950s onwards the accumulation of TOC-rich sediments also at water depths between 150 and approximately 60–70 m. The recent limit of sediment re-suspension at a water depth of approximately 60–70 m marks the modern winter-time mixing depth (determined by the halo(pycno)cline). A slight reversal to LIA conditions is seen during the late 1980s when air and water temperatures decreased and stratification weakened (Fig. 7), resulting in a decline of hypoxic areas and bottom-water ventilation restricted to sub-basins north of the Baltic Sea Klint.

The speed – within <10 years – of the environmental change triggered by external forcing (temperature and stratification) and accelerated by internal processes is remarkable. The combined effect of stratification and temperature changes, which seems to have played a stronger role than previously thought, needs to be studied also for former repeated natural marked environmental shifts (e.g. Zillén *et al.* 2008; Warden *et al.* 2017). It will be a challenge to precisely determine the rate of changes when these occur within a decade and given the uncertainties of the dating methods available. Our study also indicates that the environmental and depositional conditions, and the degree of oxygenation in the deep basins, essentially did not change during the last ~70 years and will probably not change soon as under modern climatic conditions the main contributor of phosphorous to the ecosystem will be the seabed sediment (Fig. S7C, cf. Stigebrandt & Andersson 2020).

Acknowledgements. – We thank the captains, the technical and scientific crews onboard RV 'Maria S. Merian' and RV 'Elisabeth Mann Borgese' for technical assistance in obtaining the cores during the numerous cruises. We acknowledge Sascha Plewe, Ines Scherff, Kerstin Brembach, Barbara Hentzsch, Anna-Lucia Buer, Claas Mellis, Karoline Kabel, Steffi Bednarczyk and Katharina Häusler for technical and laboratory help. The research presented in this study is also part of the Baltic Earth (Earth System Science for the Baltic Sea Region) programme (http://baltic.earth). This study also received funding from the Netherlands Earth System Science Center through a gravitation grant (024.002.001) from the Dutch Ministry for Education, Culture and Science to JSSD. We thank the two anonymous reviewers for their constructive and helpful comments, and Jan A. Piotrowski for the smooth editorial handling.

Author contributions. – The research project including several ship expeditions was designed by MM, ATK, IS, TN, KP, HEMM, HK, TL, JSSD and RS. SP contributed with hydroacoustic data recording and interpretation. Benthic foraminifera counting was performed and overseen by KP and MM. HEMM and TN focussed on oceanographic data interpretation. All authors discussed the results and conclusions of the research. MM, ATK and JSSD drafted the manuscript which was commented on by all authors.

Data availability statement. – Data sharing is not applicable to this article as no new data were created or analyzed in this study.

References

Alenius, P. & Haapala, J. 1992: Hydrographic variability in the northern Baltic in the twentieth century. *ICES Marine Science Symposium 195*, 478–485.

Alexandersson, H. & Eriksson, B. 1989: Climate fluctuations in Sweden 1860–1987. *Swedish Meteorological and Hydrological Institute Report, Meteorology and Climatology 58*, 54 pp.

Andrén, E., van Wirdum, F., Ivarsson, L. N., Lönn, M., Moros, M. & Andrén, T. 2020: Medieval versus recent environmental conditions in the Baltic Proper, what was different a thousand years ago? *Palaeogeography, Palaeoclimatology, Palaeoecology 555*, 109878, https://doi.org/10.1016/j.palaeo.2020.109878.

Binczewska, A., Moros, M., Polovodova Asteman, I., Sławińska, J. & Bąk, M. 2018: Changes in the inflow of saline water into the Bornholm Basin (SW Baltic Sea) during the past 7100 years–evidence from benthic foraminifera record. *Boreas 47*, 297–310.

Brodniewicz, I. 1965: Recent and some Holocene foraminifera of the southern Baltic Sea. *Acta Paleontologica Polonica 10*, 131–157.

Carstensen, J., Andersen, J. H., Gustafsson, B. G. & Conley, D. J. 2014: Deoxygenation of the Baltic Sea during the last century. *Proceedings of the National Academy of Sciences 111*, 5628–5633.

Conley, D. J., Humborg, C., Smedberg, E., Rahm, L., Papush, L., Danielsson, Å., Clarke, A., Pastuszak, M., Aigars, J., Ciuffa, D. & Mörth, C. M. 2008: Past, present and future state of the biogeochemical Si cycle in the Baltic Sea. *Journal of Marine Systems 73*, 338–346.

Croudace, I. W., Rindby, A. & Rothwell, R. G. 2006: ITRAX: description and evaluation of a new multi-function X-ray core scanner. *Geological Society of London, Special Publication 267*, 51–63.

Dellwig, O., Wegwerth, A. & Arz, H. W. 2021: Anatomy of the Major Baltic Inflow in 2014: impact of manganese and iron shuttling on phosphorus and trace metals in the Gotland Basin, Baltic Sea. *Continental Shelf Research 223*, 104449, https://doi.org/10.1016/j.csr.2021.104449.

Dutheil, C., Meier, H. E. M., Gröger, M. & Börgel, F. 2022: Understanding past and future sea surface temperature trends in the Baltic Sea. *Climate Dynamics 58*, 3021–3039.

Eilola, K., Almroth-Rosell, E. & Meier, H. E. M. 2014: Impact of saltwater inflows on phosphorus cycling and eutrophication in the Baltic Sea. A 3D model study. *Tellus A 66*, 23985, https://doi.org/10.3402/tellusa.v66.23985.

Fischer, H. & Matthäus, W. 1996: The importance of the Drogden Sill in the Sound for major Baltic inflows. *Journal of Marine Systems 9*, 137–157.

Fonselius, S. 1967: Hydrography of the Baltic Deep Basins II. *Fishery Board of Sweden, Series Hydrography, Report 20*, 31 pp.

Fonselius, S. 1969: Hydrography of the Baltic Deep Basins III. *Fishery Board Sweden, Series Hydrography, Report 23*, 97 pp.

Fonselius, S. & Valderrama, J. 2003: One hundred years of hydrographic measurements in the Baltic Sea. *Journal of Sea Research 49*, 229–241.

Granqvist, G. 1938: Zur Kenntnis der Temperatur und des Salzgehaltes des Baltischen Meeres an den Küsten Finnlands. *Havsforskningsinstitutets Skrift 122*, 166 pp.

Haapala, J. J., Ronkainen, I., Schmelzer, N. & Sztobryn, M. 2015: Recent change – Sea ice. *In* The BACC II Author Team (ed.): *Second Assessment of Climate Change for the Baltic Sea Basin*, 145–153. Springer, Cham.

Häusler, K., Dellwig, O., Schnetger, B., Feldens, P., Leipe, T., Moros, M., Pollehne, F., Schönke, M., Wegwerth, A. & Arz, H. W. 2018: Massive Mn carbonate formation in the Landsort Deep (Baltic Sea): hydrographic conditions, temporal succession, and Mn budget calculations. *Marine Geology 395*, 260–270.

Häusler, K., Moros, M., Wacker, L., Hammerschmidt, L., Dellwig, O., Leipe, T., Kotilainen, A. & Arz, H. W. 2017: Mid-to late Holocene environmental separation of the northern and central Baltic Sea basins in response to differential land uplift. *Boreas 46*, 111–128.

Hermelin, J. O. R. 1987: Distribution of Holocene Benthic Foraminifera in the Baltic Sea. *Journal of Foraminiferal Research 17*, 63–72.

Hille, S., Leipe, T. & Seifert, T. 2006: Spatial variability of recent sedimentation rates in the Eastern Gotland Basin (Baltic Sea). *Oceanologia 48*, 297–317.

Jilbert, T. & Slomp, C. P. 2013: Rapid high-amplitude variability in Baltic Sea hypoxia during the Holocene. *Geology 41*, 1183–1186.

Kabel, K., Moros, M., Porsche, C., Neumann, T., Adolphi, F., Andersen, T. J., Siegel, H., Gerth, M., Leipe, T., Jansen, E. & Sinninghe Damsté, J. S. 2012: Impact of climate change on the Baltic Sea ecosystem over the last 1000 years. *Nature Climate Change 2*, 871–874.

Kahru, M., Horstmann, U. & Rud, O. 1994: Satellite detection of increased cyanobacteria blooms in the Baltic Sea: natural fluctuation or ecosystem change? *Ambio 23*, 469–472.

Kaiser, J., Abel, S., Arz, H. W., Cundy, A. B., Dellwig, O., Gaca, P., Gerdts, G., Hajdas, I., Labrenz, M., Milton, J. A., Moros, M., Primpke, S., Roberts, S. L., Rose, N. L., Turner, S. D., Voss, M. & Ivar do Sul, J. A. 2022: The East Gotland Basin (Baltic Sea) as a candidate Global Boundary Stratotype Section and Point for the Anthropocene series. *The Anthropocene Review 10*, 25–48, https://doi.org/10.1177/20530196221132709.

Kniebusch, M., Meier, H. E. M., Neumann, T. & Börgel, F. 2019: Temperature variability of the Baltic Sea since 1850 in model simulations and observations and attribution to atmospheric forcing. *Journal of Geophysical Research – Oceans 124*, 4168–4187.

Kononen, K. 1992: Dynamics of the toxic cyanobacterial blooms in the Baltic Sea. *Finnish Marine Research 261*, 3–36.

Kotilainen, A., Arppe, L., Dobosz, S., Jansen, E., Kabel, K., Karhu, J., Kotilainen, M., Kuijpers, A., Lougheed, B., Meier, M., Moros, M., Neumann, T., Porsche, C., Poulsen, N., Rasmussen, P., Ribeiro, S., Risebrobakken, B., Ryabchuk, D., Schimanke, S., Snowball, I., Spiridonov, M., Virtasalo, J., Weckström, K., Witkowski, A. & Zhamoida, V. 2014: Echoes from the past – a healthy Baltic Sea requires more effort. *Ambio 43*, 60–68.

Krapf, K., Naumann, M., Dutheil, C. & Meier, H. M. 2022: Investigating hypoxic and euxinic area changes based on various datasets from the Baltic Sea. *Frontiers in Marine Science 9*, 823476, https://doi.org/10.3389/fmars.2022.823476.

Kunzendorf, H. & Larsen, B. 2009: Environmental changes in the Bornholm Basin as deduced from the geochemistry of short and long sediment cores. *Baltica 22*, 101–110.

Lenz, C., Jilbert, T., Conley, D. J., Wolthers, M. & Slomp, C. P. 2015: Are recent changes in sediment manganese sequestration in the euxinic basins of the Baltic Sea linked to the expansion of hypoxia? *Biogeosciences 12*, 4875–4894.

Liblik, T. & Lips, U. 2019: Stratification has strengthened in the Baltic Sea–an analysis of 35 years of observational data. *Frontiers in Earth Science 7*, 174, https://doi.org/10.3389/feart.2019.00174.

Lutze, G. F. 1965: Zur Foraminiferen-Fauna der Ostsee. *Meyniana 15*, 75–142.

Matthäus, W. & Franck, H. 1992: Characteristics of major Baltic inflows—a statistical analysis. *Continental Shelf Research 12*, 1375–1400.

Matthäus, W., Nehring, D., Feistel, R., Nausch, G., Mohrholz, V. & Lass, H. U. 2008: The inflow of highly saline water into the Baltic Sea. *In* Feisel, R., Nausch, G. & Wasmund, N. (eds.): *State and Evolution of the Baltic Sea, 1952–2005: A Detailed 50 Year Survey of Meteorology and Climate, Physics, Chemistry, Biology, and Marine Environment*, 265–309. John Wiley & Sons, New Jersey.

Meier, H. E. M., Eilola, K., Almroth-Rosell, E., Schimanke, S., Kniebusch, M., Höglund, A., Pemberton, P., Liu, Y., Väli, G. & Saraiva, S. 2019: Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850. *Climate Dynamics 53*, 1145–1166.

Meier, H. E. M., Feistel, R., Piechura, J., Arneborg, L., Burchard, H., Fiekas, V., Golenko, N., Kuzmina, N., Mohrholz, V., Nohr, C., Paka, V. T., Sellschopp, J., Stips, A. & Zhurbas, V. 2006: Ventilation of the Baltic Sea deep water: a brief review of present knowledge from observations and models. *Oceanologia 48*, 133–164.

Meier, H. E. M. and 46 others 2022: Climate change in the Baltic Sea region: a summary. *Earth System Dynamics 13*, 457–593.

Moberg, A. 2022: *Stockholm Historical Weather Observations—Thermometer observations since 1756. Dataset version 1. Bolin Centre Database.* https://doi.org/10.17043/stockholm-historical-thermometer-1.

Mohrholz, V. 2018: Major Baltic inflow statistics–revised. *Frontiers in Marine Science 5*, 384, https://doi.org/10.3389/fmars.2018.00384.

Moros, M., Andersen, T. J., Schulz-Bull, D., Häusler, K., Bunke, D., Snowball, I., Kotilainen, A., Zillén, L., Jensen, J. B., Kabel, K., Hand, I., Leipe, T., Lougheed, B. C., Wagner, B. & Arz, H. W. 2017: Towards an event stratigraphy for Baltic Sea sediments deposited since AD 1900: approaches and challenges. *Boreas 46*, 129–142.

Moros, M., Kotilainen, A. T., Snowball, I., Neumann, T., Perner, K., Meier, H. M., Leipe, T., Zillén, L., Sinninghe Damsté, J. S. & Schneider, R. 2020: Is 'deep-water formation' in the Baltic Sea a key to understanding seabed dynamics and ventilation changes over the past 7,000 years? *Quaternary International 550*, 55–65.

Moros, M., Lemke, W., Kuijpers, A., Endler, R., Jensen, J. B., Bennike, O. & Gingele, F. 2002: Regressions and transgressions of the Baltic basin reflected by a new high resolution deglacial and postglacial lithostratigraphy for Arkona Basin sediments (western Baltic Sea). *Boreas 31*, 151–162.

Neumann, T., Christiansen, C., Clasen, S., Emeis, K. C. & Kunzendorf, H. 1997: Geochemical records of salt water inflows into the deep basins of the Baltic Sea. *Continental Shelf Research 17*, 95–115.

Neumann, T., Heiser, U., Leosson, M. A. & Kersten, M. 2002: Early diagenetic processes during Mn-carbonate formation: evidence from the isotopic composition of authigenic Ca-rhodochrosites of the Baltic Sea. *Geochimica et Cosmochimica Acta 66*, 867–879.

Neumann, T., Radtke, H. & Seifert, T. 2017: On the importance of Major Baltic Inflows for oxygenation of the central Baltic Sea. *Journal of Geophysical Research – Oceans 122*, 1090–1101.

Olofsson, M., Egardt, J., Singh, A. & Ploug, H. 2016: Inorganic phosphorus enrichments in Baltic Sea water have large effects on growth, carbon fixation, and N_2 fixation by *Nodularia spumigena*. *Aquatic Microbial Ecology 77*, 111–123.

Ponomarenko, E. P. & Krechik, V. A. 2018: Benthic foraminifera distribution in the modern sediments of the southeastern Baltic Sea with respect to North Sea water inflows. *Russian Journal of Earth Sciences 18*, 1–7.

Radtke, H., Brunnabend, S.-E., Gräwe, U. & Meier, H. E. M. 2020: Explaining interdecadal salinity changes in the Baltic Sea in a 1850-2008 hindcast simulation. *Climate of the Past 16*, 1617–1642.

Soskin, I. M. 1963: *Mnogoletniye izmeneniya gidrologicheskikh kharakteristik Baltiyskogo Morya*. Gidrometeorologicheskoye Yzdatel'stvo, Leningrad (in Russian).

Stal, L. J., Staal, M. & Villbrandt, M. 1999: Nutrient control of cyanobacterial blooms in the Baltic Sea. *Aquatic Microbial Ecology 18*, 165–173.

Stigebrandt, A. 1985: A model for the seasonal pycnocline in rotating systems with application to the Baltic proper. *Journal of Physical Oceanography 15*, 1392–1404.

Stigebrandt, A. & Andersson, A. 2020: The eutrophication of the Baltic Sea has been boosted and perpetuated by a major internal phosphorus source. *Frontiers in Marine Science 7*, 572994, https://doi.org/10.3389/fmars.2020.572994.

Sverdrup, H. U., Johnson, M. W. & Fleming, R. H. 1942: *The Oceans: Their Physics, Chemistry, and General Biology*. 1087 pp. Prentice-Hall, New York.

Tuuling, I. & Flodén, T. 2016: The Baltic Klint beneath the central Baltic Sea and its comparison with the North Estonian Klint. *Geomorphology 263*, 1–18.

Vahtera, E., Conley, D. J., Gustafsson, B. G., Kuosa, H., Pitkänen, H., Savchuk, O. P., Tamminen, T., Viitasalo, M., Voss, M., Wasmund, N. & Wulff, F. 2007: Internal ecosystem feedbacks enhance nitrogen-fixing cyanobacteria blooms and complicate management in the Baltic Sea. *AMBIO: A Journal of the Human Environment 36*, 186–194.

Van Wirdum, F., Andrén, E., Wienholz, D., Kotthoff, U., Moros, M., Fanget, A. S., Seidenkratz, M. S. & Andrén, T. 2019: Middle to late Holocene variations in salinity and primary productivity in the central Baltic Sea: a multiproxy study from the Landsort Deep. *Frontiers in Marine Science 6*, 51, https://doi.org/10.3389/fmars.2019.00051.

Warden, L., Moros, M., Neumann, T., Shennan, S., Timpson, A., Manning, K., Sollai, M., Wacker, L., Perner, K., Häusler, K., Leipe, T., Zillen, L., Kotilainen, A., Jansen, E., Schneider, R. R., Oeberst, R., Arz, H. & Sinninghe Damsté, J. S. 2017: Climate induced human demographic and cultural change in northern Europe during the mid-Holocene. *Scientific Reports 7*, 15251, https://doi.org/10.1038/s41598-017-14353-5.

Wasmund, N. 1997: Occurrence of cyanobacterial blooms in the Baltic Sea in relation to environmental conditions. *Internationale Revue der Gesamten Hydrobiologie und Hydrographie 82*, 169–184.

Wasmund, N., Pollehne, F., Postel, L., Siegel, H. & Zettler, M. L. 2004: Biologische Zustandseinschätzung der Ostsee im Jahre 2003. *Marine Science Reports Warnemünde 60*, 87 pp.

Wefer, G. & Lutze, G. F. 1978: Carbonate production by benthic foraminifera and accumulation in the western Baltic 1. *Limnology and Oceanography 23*, 992–996.

Zillén, L., Conley, D. J., Andrén, T., Andrén, E. & Björck, S. 2008: Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact. *Earth-Science Reviews 91*, 77–92.

Supporting Information

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Fig. S1. XRF scanner manganese (Mn – black) and potassium (K – grey), mercury (Hg – purple), benthic foraminifera (tests per gram – blue) and radionuclide (^{137}Cs – black, ^{241}Am – orange) data from multi-cores shown in Fig. 3 plus four additional cores (MSM99-182, -31, -188 and -09) from the Eastern Gotland Basin (EGB), Northern Central Basin (NCB) and Fårö Deep (FD). Important stratigraphic markers are indicated: AD 1986 Chernobyl; 1963 – bomb test maximum. The massive saline water inflow AD 1951 is marked in the foraminiferal record. A dashed horizontal black line shows the depth position of the marked sedimentological change.

Fig. S2. XRF scanner manganese (Mn – black) and potassium (K – grey), mercury (Hg – purple), benthic foraminifera (tests per gram – blue) and radionuclide (^{137}Cs – black, ^{241}Am – orange) data from multi-cores shown in Fig. 3 plus three additional cores (MSM99-17 and -18 and MSM62-54) from the Eastern Gotland Basin (EGB), Landsort Deep (LD) and Western Gotland Basin (WGB). Important stratigraphic markers are indicated: AD 1986 – Chernobyl; 1963 – bomb test maximum. The massive saline water inflow AD 1951 is marked in the foraminiferal record. A dashed horizontal black line shows the depth position of the marked sedimentological change. Note the rather high sedimentation rate at the sites MSM99-18 taken in a rather shallow marginal basin of the Eastern Gotland Basin (Fig. 4).

Fig. S3. Hydroacoustic PARASOUND profile NCB-1 (location see map) with multi-corer stations from the Northern Central Basin including the Baltic Sea Klingt. Multi-cores were taken on a water depth transect from c. 190 to 65 m. A peak in mercury profiles (Hg – pink) marks the pollution maximum of the 1960s/1970s (Moros *et al.* 2017). A dashed horizontal black line shows the depth position of the marked sedimentological change. Typically, complete sediment sequences are found only below c. 150–160 m water depth, the base of sediment re-suspension during the Little Ice Age until the early 1950s (sites MSM99-20 and -22). Since the mid to late 1950s organic carbon-rich sediments also accumulated on top of old Baltic Ice Lake sediments up to a water level of 60–70 m, the modern winter-time mixing depth (sites MSM99-21 and -23). There is no fine-grained sediment (or fluff) above the modern winter mixing depth (site MSM99-24). Note that manganese-carbonate layer formation is found in a channel-like structure (site MSM99-22) probably forming the path for northerly formed oxygenated bottom water in the late 1980s. CTD profiles from two stations obtained in February 2021 (see map) evidence that a sill just south of the Åland Deep forms the modern border (red dashed line) between anoxic (site MSM99-34) and oxic bottom waters (site MSM99-38). In the 1980s this hydrographic barrier was formed by the Baltic Sea Klint.

Fig. S4. Hydroacoustic PARASOUND profile NCB-2 (location see map) with multi-corer stations from the Northern Central Basin. Multi-cores were taken on a water depths transect from ~175 to 66 m. A peak in the sedimentary mercury records (Hg – pink) marks the pollution maximum of the 1960s/1970s (Moros *et al.* 2017). A dashed horizontal black line shows the depth position of the marked sedimentological change. Typically, complete sediment sequences are found only below ~150–160 m water depth (at MSM99-30, -31), the base of sediment re-suspension during the Little Ice Age until the early 1950s. Since the mid to late 1950s organic carbon-rich sediments also accumulated on top of old Baltic Ice Lake (BIL) sediments up to a water level of 60–70 m, the modern winter-time mixing depth (sites MSM99-29, -28 and -27). There is no fine-grained sediment above the modern winter mixing depth (site MSM99-26).

Fig. S5. Hydroacoustic PARASOUND profile from the Bornholm Basin (Moros *et al*. 2020) with two multicorer stations sampled during cruise MSM99. Multicores were taken at water depths deeper than 60–70 m. A sharp incease in the sedimentary mercury records (Hg – pink) marks the pollution maximum of the 1960s/1970s (Moros *et al*. 2017). Additional time markers are: (i) AD 1963 nuclear weapons test maximum as peaks in ^{241}Am (orange) and ^{137}Cs (black) records; and (ii) AD 1986 Chernobyl – sharp increase in ^{137}Cs (black). Typically, since probably the mid to late 1950s organic carbon-rich sediments have started to accumulate also on top of old Baltic Ice Lake (BIL) sediments at a water depth of 95 m (MSM99-05). Note the sharp increase in Hg in MSM99-06 indicating that the sedimentation was not continuous.

Fig. S6. Critical hydrographic time series data (all modified after Fonselius 1969) which illustrate the effect of the massive saline water inflow AD 1951. A marked drop in oxygen occurred shortly after the inflow in the deeper water layers of e.g. Landsort Deep (A), Northern Central Basin (B) and Western Gotland Basin (C) and is accompanied by phosphate increase (C) from the sediment (Fonselius 1967). The AD 1951 inflow increased the stability of the 50–100 m water layer to a maximum, here exemplified from the Landsort Deep (E).

Fig. S7. Critical hydrographic measurements evidencing a stepwise salinity increase in the Baltic Sea during the first half of the 20th century (A, modified after Soskin 1963). Our new results clearly confirm Fonselius's significant statements made in 1969 (B). (C) The results of Stigebrand and Andersson (2020) indicate that internal phosphorus (P) is more critical than the land-based P source for the concentration of P in surface waters that influences primary production and finally the extent of hypoxic/anoxic areas. The approximate timing of the marked sedimentological change focussed on in the present paper is shown by a vertical dashed line in C.

Table S1. Details on the multi-core (MC, core length), CTD (italic) and monitoring (Mst, data downloaded from the Swedish Meteorological and Hydrological Institute database) sites studied located in all subbasins of the Baltic proper (see Fig. 1 for a map). In addition, the location of three hydroacoustic PARASOUND profiles (EGB, NCB-1, NCB-2) shown and discussed in this paper are presented. Radionuclide and mercury data of M86/1-36(**) and MSM62-59(*) were first published by Häusler *et al*. (2018) and Andrén *et al*. (2020), respectively. Time marker positions from cores 377 860 and part of MSM51-15 were published in Moros *et al*. (2017).