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Biological assessment of the Baltic Sea 2023

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Kurzfassung

Im Jahr 2023 beeinflussten eine Reihe von Einstromereignissen die **Umweltbedingungen** in den verschiedenen Becken der westlichen Ostsee. Spuren des kalten, salzreichen Einstromes vom Dezember 2022 waren noch im Februar 2023 im Bodenwasser des Arkonabeckens sichtbar. Im Frühsommer führte ein barokliner Einstrom in der Beltsee zu einer salzreichen Bodenwasserschicht und ersetzte das kalte Bodenwasser im Arkonabecken durch warmes, aber nicht außergewöhnlich salzhaltiges Wasser. Im Dezember 2023 wurde eine verstärkte Einstromaktivität registriert, die als mittelgroßer Major Baltic Inflow (MBI) eingestuft wurde. 2023 wies das Oberflächenwasser in der westlichen Ostsee (Darsser Schwelle und Arkona-Boje) Temperaturen auf, die über dem langjährigen Durchschnitt lagen. Im Winter und Herbst lagen die Oberflächenwassertemperaturen etwa 1,5 K über dem langjährigen Durchschnitt. Die Sommertemperaturen glichen dem langjährigen Durchschnitt, mit gelegentlichen Abweichungen aufgrund von Kälteanomalien im Juni und August, die wahrscheinlich durch episodische Auftriebsereignisse verursacht wurden. Die teilweise kühle und stürmische Witterung im Sommer 2023 sowie der Einstrom im Dezember 2022 führten zu einer gleichbleibend guten Sauerstoffversorgung von der Beltsee bis zur Arkonasee (Bodenwasser › 2 ml l^{-1}). Die Konzentrationen der anorganischen Nährstoffe im Oberflächenwasser lagen im Februar 2023 im Bereich der vorherigen Dekade. Das N/P-Verhältnis des Oberflächenwassers zeigte einen abnehmenden West-Ost-Trend von der Beltsee zur Bornholmsee. Dieses Muster ähnelte dem des Vorjahres und bestätigte erneut, dass Stickstoff ein begrenzender Faktor in der zentralen Ostsee ist, der diazotrophen Cyanobakterien einen Vorteil gegenüber Primärproduzenten verschafft, die auf Nitrat angewiesen sind.

2023 wurden auf 5 Monitoringausfahrten insgesamt 29 **Phytoplankton**proben an 6 Stationen in der Belt See (Kieler Bucht und Mecklenburger Bucht) und im Arkona Becken genommen. 2023 betrug die mittlere jährliche Biomasse im Untersuchungsgebiet 593,23 µg l^{-1}. Sie war damit erheblich geringer als im Vorjahr und blieb unter dem 20-Jahresmittelwert. Die entsprechende mittlere Chlorophyll *a* (Chl *a*) Konzentration von 2,81 µg l^{-1} bewegte sich hingegen in der Größenordnung der vergangenen Jahre. Die jahreszeitliche Chl *a* Dynamik war an allen Stationen der beiden Seegebiete ähnlich. Die höchsten Chl *a* Konzentrationen wurden jeweils im März und November gemessen, wobei Spitzenkonzentrationen von 13 µg l^{-1} im März an Station N3 in der Kieler Bucht auftraten. Die Phytoplanktonbiomasse wies dort mit 4636 µg l^{-1} ebenfalls die höchste Konzentration des Jahres auf. Trotz der generell sehr ähnlichen jahreszeitlichen Chl *a* Sukzessionsmuster in beiden untersuchten Seegebieten unterschied sich die Biomassedynamik des Phytopanktons erheblich. Sie spiegelte den zunehmenden Einfluss der niedrigsalinen Ostsee wider. Die Frühjahrsblüte der Diatomeen in der Belt See begann in der Kieler Bucht bereits im Februar, als eine Chl *a* Konzentration von 3 µg l^{-1} und eine Biomasse von 362 µg l^{-1} gemessen wurden. Die Phytoplanktongemeinschaft bestand zu diesem Zeitpunkt zum großen Teil aus Diatomeen, insbesondere *Rhizosolenia* spp., die hier mehr als 70 % der Biomasse ausmachte. Wenige Wochen später im März hatte sich die Phytoplanktonbiomasse in der Kieler Bucht verzehnfacht. Dem gegenüber war das Phytoplanktonwachstum in der Mecklenburger Bucht leicht verzögert und die Biomassekonzentrationen generell wesentlich niedriger. Diatomeen waren hier zu diesem Zeitpunkt weiterhin die dominierende Phytoplanktongruppe, jedoch machten auch *Mesodinium rubrum* (Ciliophora) und sein Beuteorganismus *Teleaulax*

(Cryptophyta) einen recht hohen Biomasseanteil aus. Auch die Phytoplankton Sommergemeinschaft der Mecklenburger Bucht war sehr stark von Diatomeen geprägt, was einen marinen Einfluss zu diesem Zeitpunkt nahelegt. Jedoch machten im August auch Dinoflagellaten, insbesondere der Gattung *Tripos*, und Cyanobakterien größere Biomasseanteile aus. Der Spätherbst, repräsentiert durch die Novemberfahrt, war 2023 die Zeit der höchsten Phytoplanktonproduktion in der Mecklenburger Bucht mit Chl *a* Konzentrationen von 4,3 bis 8 µg l^{-1} und Biomassen von bis zu 1390 µg l^{-1}. Im Arkona Becken war die räumliche Ausbreitung der Frühjahrsblüte in Richtung Nordosten gut in den Phytoplanktondaten repräsentiert. Die höchsten Chl *a* Konzentrationen des Jahres (6,3 µg l^{-1} an Station K5 und 3,6 µg l^{-1} an K4) und entsprechende Biomassekonzentrationen (1168 µg l^{-1} an K5 und 228,5 µg l^{-1} an K4) wurden im November im westlichen und zentralen Arkonabecken gemessen. Winter- und Frühjahrs- Chl *a* -Konzentrationen folgten dem typischen räumlichen Muster der Abnahme in Richtung Nordosten. Die Arkona-Phytoplanktongemeinschaft war 2023 generell stark von *Mesodinium rubrum* geprägt, insbesondere im Frühling. Dinoflagellaten und Cyanobakterien waren mit Biomasseanteilen von 45 % und 20 % recht stark in der Sommergemeinschaft vertreten. Im November war die Arkonagemeinschaft marin geprägt und wurde von Diatomeen wie *Cerataulina bergonii* und *Rhizosolenia fragilissima* dominiert.

Im Jahr 2023 wurden insgesamt 141 Phytoplankton-Taxa auf den Monitoringstationen der Belt- und Arkona See erfasst. Die Anzahl der Taxa war mit 81 im November am höchsten. Wie auch in den Vorjahren, waren 2023 Diatomeen die prominentesten Phytoplanker in der südlichen Ostsee. Insbesondere *Rhizosolenia* spp., *Proboscia alata* und *Cerataulina bergonii* waren die wichtigsten Biomasseproduzenten des Jahres 2023 in der Belt See (50 - 90 %), häufig begleitet von Dinoflagellaten (*Tripos muelleri* und *Polykrikos schwartzii*). Im Arkona Becken war *Mesodinium rubrum* die häufigste Art auf allen Monitoringfahrten.

Auf den 5 Monitoringausfahrten des Jahres 2023 wurde, im Vergleich zum Vorjahr, mit 15 Arten eine höhere Anzahl von potentiell toxischen oder anderweitig schädlichen Phytoplankton-Taxa als 2022 (8 Arten) erfasst. Auf der Liste befanden sich nun auch einige Warmwasserarten wie *Karenia mikimotoi*, *Akashiwo sanguinea* und *Karlodinium veneficum*. Die Cyanobakterienbiomasse (Cyabi), die zur Zustandseinschätzung der Ostsee herangezogen wird, wurde erstmals im Langzeitkontext für die Belt- und Arkonastationen in einem Zeitraum von 20 Jahren betrachtet. Während 2023 in der Belt See die Cyanobakterienbiomassen an den Stationen im Bereich des 20-Jahresmittelwertes oder darunter lagen, waren sie im östlichen Arkonabecken höher als der 20-Jahresmittelwert.

Im Jahr 2023 wurde das **Zooplankton** an 38 Stationen in der Kieler Bucht, der Mecklenburger Bucht und dem Arkonabecken beprobt. Im Gegensatz zu den Vorjahren wurde die hydrographische Situation durch eine Reihe von Einstromereignissen beeinflusst, die den Salzgehalt in der Wassersäule der Beltsee und des Bodenwassers im Arkonabecken erhöhten, aber auch zu sehr warmen Wassertemperaturen im gesamten Gebiet im Sommer führten. Die Einstromereignisse hatten jedoch nur einen geringen Einfluss auf das Arteninventar, da die Anzahl der Taxa in der Größenordnung der Vorjahre ohne größere Einstromereignisse lag (52 Taxa). Zwar wurde der Transport einiger stenohaliner mariner Taxa wie *Penilia avirostris* in das Arkonabecken beobachtet, ihre Anzahl war jedoch gering. Darüber hinaus fehlten im Jahr 2023 mehrere marine und Brackwasserarten, die in den vorangegangenen Jahren vorkamen, so dass die Anzahl der Taxa auf einem niedrigeren Niveau blieb. Abgesehen von *Acartia tonsa* wurden keine weiteren Arten beobachtet, die als nicht-einheimische Arten (NIS) eingestuft wurden.

Die Artenzusammensetzung im Jahresdurchschnitt wurde in allen Gebieten von Copepoda dominiert. Dies ist in der Beltsee üblich, aber ungewöhnlich im Arkonabecken, wo Rotifera und Cladocera im Frühjahr bzw. Sommer große Bestände aufweisen können, die 2023 fehlten. Dieser Rückgang setzt eine Reihe ähnlicher Beobachtungen seit 2019 fort und kann daher nicht auf die ungewöhnliche hydrographische Situation im Jahr 2023 zurückgeführt werden. Die Abundanz des Meroplanktons war in allen Gebieten eher gering, insbesondere während des Sommers, in dem Muschel- und Schneckenlarven gewöhnlich sehr häufig sind. In der Beltsee wurden sie durch Polychaeta Larven als häufigste Gruppe ersetzt.

Die jahreszeitliche Dynamik und die Zusammensetzung des Zooplanktonbestandes in der Kieler Bucht und in der Mecklenburger Bucht waren aufgrund ihrer Verbindung über den Fehmarnbelt sehr ähnlich. In Übereinstimmung mit den Winter-Frühjahrstemperaturen, die 2-3 °C über dem langjährigen Mittel lagen, zeigte der Zooplanktonbestand einen frühen Anstieg mit einer Verdoppelung der Bestandsgröße im März bzw. Mai. Copepoda, insbesondere die Gattungen *Pseudocalanus* und *Oithona*, dominierten das Zooplankton, gefolgt von Polychaeta-Larven und der Appendicularia *Oikopleura*. Im Sommer wurde ein starker Einbruch des Zooplanktonbestandes auf 15-25 % des langjährigen Mittelwertes beobachtet. Da der Salzgehalt und die thermischen Bedingungen für diese Gebiete jedoch nicht außergewöhnlich waren, könnte der Rückgang auf einen kombinierten Stress von hohen Wassertemperaturen in Verbindung mit einem Nahrungsmangel während der Sommerperiode zurückzuführen sein. Dies wird durch die Zusammensetzung der Gemeinschaft bestätigt, in der *Oithona* und thermophile Arten dominierten. Der Zooplanktonbestand erholte sich mit der Abkühlung im Herbst, allerdings mit nur geringen Auswirkungen auf die Zusammensetzung der Gemeinschaft. Trotz der unterschiedlichen Hydrographie mit einem niedrigeren Salzgehalt in der gesamten Wassersäule ähnelten die jahreszeitliche Dynamik und die Bestandszusammensetzung des Zooplanktons im Arkonabecken denen, die auch in der Beltsee beobachtet wurden. Die Frühjahrsentwicklung war früh und wurde durch eine hohe Abundanz der Appendicularia *Fritillaria* im März verursacht. Wie üblich folgte die Zunahme der Copepoda von März bis Mai. Sie dominierten das Zooplankton im Frühjahr, da Rotifera ungewöhnlich selten waren und 2023 kein Massenvorkommen dieser Gruppe auftrat. Unter den Copepoda dominierte *Pseudocalanus*, aber auch andere Gruppen waren häufig. Auch im Arkonabecken wurde ein ungewöhnlicher Zusammenbruch des Zooplanktonbestandes im Sommer beobachtet, der mit einer geringen Abundanz von Copepoda und Cladocera einherging und wahrscheinlich durch die hohen Temperaturen in der gesamten Wassersäule verursacht wurde.

Der sommerliche Zusammenbruch des Zooplanktonbestandes in allen Gebieten hatte nur geringe Auswirkungen auf die langfristigen Schwankungen der Copepoda in der westlichen Ostsee. In der Beltsee und im Arkonabecken lag ihre jährliche mittlere Abundanz nahe dem langfristigen Mittelwert, was auf die frühe Bestandsentwicklung und die hohe Abundanz im Frühjahr zurückzuführen ist, die den Rückgang im Sommer teilweise kompensierten. Im Gegensatz zu den Copepoda wiesen die Cladocera und insbesondere die Rotifera im Jahresmittel eine eher geringe Abundanz auf. In ihrem Hauptvorkommensgebiet (Arkonabecken) sank ihr Beitrag zum Bestand auf nur 12-17 % ihres langjährigen Mittelwerts.

Im Herbst 2023 erfolgte die Beprobung des **Makrozoobenthos** an allen 8 Stationen entlang der deutschen Ostseeküste, beginnend in der Kieler Bucht über die Mecklenburger Bucht, die Darßer Schwelle, das Arkona Becken bis hin zur Pommernbucht. Für die meisten Stationen steht ein umfangreicher Datensatz von Herbstbeprobungen seit 1980 für die Langzeitanalyse zur Verfügung. Die insgesamt 138 Arten, die 2023 im Makrozoobenthos gefunden wurden, stellen eine relativ hohe Vielfalt dar. Die Anzahl der Arten, die jeweils an den acht Messstationen gefunden wurden, schwankte zwischen 16 und 86. Im Vergleich zum langjährigen Mittel konnte somit an allen Stationen eine durchschnittliche Artenzahl gefunden werden. Einzig in der Kieler Bucht wurde mit 86 Taxa eine überdurchschnittlich hohe Diversität festgestellt. An einigen Stationen wurden jedoch neue Arten (die in den letzten 20 Jahren an diesen Stationen nie beobachtet wurden) gefunden, z. B. *Philine punctata*. In allen Regionen ohne Ausnahme war das Sauerstoffangebot im Bodenwasser im laufenden Jahr höher als 2 ml l^{-1}. Je nach Region reichten die Abundanzen von 331 bis 6775 Ind. m^{-2} und die Biomasse (aschefreies Trockengewicht) von 1,8 g m^{-2} bis 25,2 g m^{-2}.

Am Beispiel der Station K4 (Arkona Becken) führten wir eine Langzeitanalyse der letzten 4 Jahrzehnte durch. Dargestellt wird die langfristige Entwicklung von Artenzahl, Abundanz und Biomasse. Zur Einordnung der Ergebnisse wurden auch die Sauerstoff- und Salzgehaltswerte am Boden über diesen Zeitraum ausgewertet und teilweise dargestellt. Anhand ausgewählter Arten (*Diastylis rathkei* und *Macoma balthica*) wird exemplarisch gezeigt, welche Veränderungen stattgefunden haben und welchen Einfluss sie auf das Ökosystem haben können. Zum zweiten Mal (nach 2021) wurden die Langzeitdaten zur Berechnung des Benthic Quality Index (BQI) und damit auch des ökologischen Zustands herangezogen. Die Hälfte der Stationen befand sich im Laufe der Jahre in einem „guten" Zustand. Drei sind im Laufe der Jahre immer als „schlecht" bewertet worden, eine weitere zwischen "schlechtem" und „gutem" Zustand.

An den acht Messstationen wurden insgesamt 19 Arten der Roten Liste Deutschlands (Kategorien 1, 2, 3 und G) beobachtet. Hervorzuheben wären hierbei neben regelmäßig anzutreffenden Arten wie beispielsweise *Arctica islandica* und Arten der Gattung *Astarte*, auch etwas seltener zu beobachtende Taxa wie *Musculus discors*, *Aporrhais pespelecani*, *Tritia reticulata* und *Scalibregma inflatum*.

Mit 10 war die Zahl der invasiven benthischen Arten 2023 relativ hoch. Die meisten waren bereits aus den Vorjahren bekannt. *Mya arenaria* und *Amphibalanus improvisus* sind seit mehr als hundert Jahren in der südlichen Ostsee häufig. Seit 2016 ist der Amphipode *Grandidierella japonica* aus der südlichen Ostsee bekannt und wurde auch während der vorliegenden Studie in der Kieler Bucht beobachtet. Die beiden Polychaeten *Alitta succinea* und *Marenzelleria neglecta* wurden in den letzten Jahren regelmäßig bei Probenahmen gefunden. Die Muschel *Ensis leei*, eine nordamerikanische Art, wurde 2023 zum ersten Mal auf der Darßer Schwelle (K8) nachgewiesen. Im westlichen Teil der Ostsee wird sie dagegen regelmäßiger, aber stets in geringen Dichten angetroffen. Der japanische Ranzenkrebs *Nippoleucon hinumensis* ist seit 2019 für die Ostsee beschrieben. Neben mehreren Nachweisen, die wir in anderen Kampagnen in der deutschen Ostsee (vor allem in Ästuaren) gemacht haben, fanden wir ihn in diesem Jahr zum ersten Mal bei Monitoring-Probenahmen in der Kieler Bucht (N3). In den letzten zehn Jahren haben wir an unseren acht Messstationen insgesamt 16 nicht-einheimische Arten (NIS) gefunden. Der langfristige Trend der letzten 10 Jahre bei den Ankünften lag bei 0,8 NIS pro Jahr.

Abstract

In 2023, a series of inflow events affected the **environmental conditions** in the different basins of the western Baltic Sea. Traces of a cold, saline inflow in December 2022 were still visible in the bottom water of the Arkona Basin during February. In early summer, a baroclinic inflow build a thick bottom layer of saline water in the Belt Sea and replaced the cold bottom water in the Arkona Basin by very warm, but not exceptionally saline water. During December 2023 intensified inflow activity was recorded, which was classified as midsized Major Baltic Inflow (MBI). In 2023, the surface waters in the western Baltic Sea (Darss Sill and Arkona Buoy) exhibited temperatures significantly higher than the long-term average. The winter and autumn water temperatures were about 1,5 K above the long-term average. Summer temperatures, however, remained close to the long-term average, with occasional deviations due to cold anomalies in June and August, likely caused by episodic upwelling events. The partly cool and stormy weather in summer 2023 as well as the minor barotropic inflow event of December 2022 resulted in a consistently good oxygen supply from the Belt Sea to the Arkona Sea (bottom water › 2 ml l^{-1}). The concentration of inorganic nutrients in the surface water was within the range of the previous decade in February 2023. The N/P ratio of the surface water showed a decreasing west-east trend from the Belt Sea to the Bornholm Sea. This pattern was similar to the previous year and confirmed again that nitrogen was a limiting factor in the Baltic Proper, giving diazotrophic cyanobacteria an advantage compared to primary producers that depend on nitrate.

In 2023, 29 **phytoplankton** samples were collected on 5 monitoring cruises from 6 stations located in the Belt Sea (Kiel Bight and Bay of Mecklenburg) and the Arkona Basin. In 2023, mean annual biomass in the study area was 593,2 µg l^{-1}. This is significantly lower than in 2022, and below the 20 year mean. Corresponding mean chlorophyll *a* (Chl *a*) concentrations of 2,8 µg l^{-1} were, however, in the range of previous years. Generally, seasonal Chl *a* dynamics was uniform and very similar in Belt Sea and Arkona Basin throughout the year, with highest concentrations measured in March and November and lowest in May. The prominent 2023 Chl *a* peak was detected in March in Kiel Bight and amounted to 13 µg l^{-1}, capturing a fully developed spring bloom. Accordingly, the highest annual phytoplankton biomass (4636 µg l^{-1}) for 2023 was detected. Despite quite uniform Chl *a* succession patterns in both sea areas, seasonal dynamics of phytoplankton biomass composition clearly displayed spatial differences along the monitoring transect, reflecting the marine influence in the Belt Sea and the increasingly brackish character of the Arkona Basin. The diatom spring bloom in the Belt Sea started in the westernmost Kiel Bight in February, when Chl *a* concentrations of nearly 3 µg l^{-1} corresponding to biomass of 362 µg l^{-1}, were measured, mostly consisting of diatoms, with *Rhizosolenia spp.* constituting › 70 %. A few weeks later, biomass of diatoms had increased more than 10-fold in the Kiel Bight. In contrast, phytoplankton production was slightly delayed in the Bay of Mecklenburg and generally had significantly lower biomass values. The community here was still dominated by diatoms but with significant contribution of *Mesodinium rubrum* and its cryptophyte prey *Teleaulax*. Also, the summer community in the Bay of Mecklenburg was highly dominated by diatoms, though portions of dinoflagellates, *Tripos*, and cyanobacteria had increased then. Late autumn (November) was the most productive period of the annual phytoplankton cycle in the Bay of Mecklenburg in 2023, as indicated by Chl *a* concentrations of 4,3 µg l^{-1} to 8 µg l^{-1} and diatom dominated (› 80 %) biomass concentrations of up to 1390 µg l^{-1}.

In Arkona Basin, the north-east succession of the spring bloom was well reflected by spatial biomass dynamics. Highest annual Chl *a* (6,3 µg l^{-1} at K5 and 3,6 µg l^{-1} at K4) and biomass concentrations (1168 µg l^{-1} at K5 and 228,5 µg l^{-1} at K4) were measured in the western and central parts of the Arkona Basin in November. Winter and spring Chl *a* concentrations decreased prominently towards the east as did biomasses. In spring, the Arkona community was generally dominated by *Mesodinium rubrum*. Dinoflagellates and cyanobacteria had high biomass shares (45% and 20 %) in August. The phytoplankton of the Arkona Basinhad a marine character in November, being dominated by the diatoms *Cerataulina bergonii* and *Rhizosolenia fragilissima.*

In 2023, alltogether 141 phytoplankton taxa were recorded in the Belt Sea and the Arkona Basin at the five monitoring cruises with highest number of taxa (89) recorded in November. As in previous years, diatoms of *Rhizosolenia spp.*, *Proboscia alata* and *Cerataulina bergonii* were the most important biomass producers in Belt Sea in March, August, and November (50 - 90 %) often accompanied by the dinoflagellates *Tripos muelleri* and *Polykrikos schwartzii*. In Arkona Basin the *Mesodinium rubrum* ranked number 1 (3 for all samples, Appendix) at all three cruises in spring, contributing up to 81 % in February. In summer and autumn, diatoms were unexpectedly prominent. Thus, while the spring community was a typical brackish Baltic one, the summer and autumn aspects had a clearly marine character.

In 2023, the number of potentially toxic or harmful algal taxa recorded in the study area had increased to 15 (compared to xy taxa in 2022). The list now contains several warm-water species such as *Karenia mikimotoi*, *Akashiwo sanguinea* and *Karlodinium veneficum*. Cyanobacteria biomass (Cyabi) of 2023 was, for the first time, considered in a long-term analysisfor the Belt Sea and the Arkona Basin: Whereas in the Belt Sea Cyabi was at the 20 year mean, it was above the 20 year mean at the central and Eastern Arkona stations.

In 2023, **zooplankton** samples were taken on 38 stations in the Kiel Bight, the Bay of Mecklenburg and the Arkona Basin. In contrast to previous years, the hydrographical situation was influenced by a series of inflow events that elevated the salinity in the water column in the Belt Sea and the bottom water in the Arkona Basin, but caused also very warm water temperatures throughout the area during summer. The inflows had, however, only little influence on the species inventory since the number of taxa were in the range of previous years without large inflow events (52 taxa). While a transport of some stenohaline marine taxa such as *Penilia avirostris* into the Arkona Basin was observed, their number was low. In addition, several of the marine and brackish species that were present in preceding, non-inflow years were lacking in 2023 and, thus, the taxa number remained on a lower level. Apart from *Acartia tonsa*, no other species classified as non-indigenous species (NIS) were observed.

The annual average species composition was dominated by copepods in all areas. This is common in the Belt Sea, but unusual in the Arkona Basin where rotifers and cladocerans can show large stocks in spring and summer, respectively. These were lacking in 2023. The decline in their contribution continues a series of similar observations since 2019 and, thus, cannot be attributed to unusual hydrographical situation in 2023. The meroplankton abundance was also rather low in all areas, particularly during summer when bivalve and gastropod larvae are common. In the Belt Sea, they were replaced by polychaete larvae as the most common group.

The seasonal dynamics and the composition of the zooplankton stock in the Kiel Bight and the Bay of Mecklenburg was very similar likely owed to their connection via the Fehmarn Belt. In agreement with winter-spring temperatures that were 2-3 °C above the long-term mean, the zooplankton stock showed an early increase with a doubling of the stock size in March and May, respectively. Copepods, especially the genera *Pseudocalanus* and *Oithona*, dominated the zooplankton followed by polychaete larvae and the appendicularian *Oikopleura*. In summer, the zooplankton stock collapsed to only 15-25 % of the long-term mean. Since the saline and thermal conditions were not exceptional for the area, the decline might be related to a combined stress of very warm temperaturates together with the usual food shortage during the summer period. This is reinforced by the composition of the community that was dominated by *Oithona* and other, thermophilic species. The stock recovered with the cooling in autumn, but with only little effects on the community composition. Despite the different hydrography with a lower salinity throughout the water column, the seasonal dynamics and stock composition of the zooplankton in the Arkona Basin resembled those observed in the Belt Sea. The spring development was early and was caused by a high abundance of the appendicularian *Fritillaria* in March. As usual, the increase in the copepods followed from March to May. They dominated the zooplankton in spring because rotifers were rather rare and lacked the sometimes typical mass concentrations in 2023. *Pseudocalanus* dominated among the copepods, but other groups were common as well. Again, an unusual collapse of the zooplankton in summer was observed that was associated a with low abundance of copepods and cladocerans. This was likely caused by the high temperatures throughout the water column.

The summer collapse of the zooplankton in all areas had only little impact on the long-term variation of the copepods in the western Baltic Sea. In the Belt Sea and the Arkona Basin, their annual mean abundance was close the long-term mean, which can be attributed to the early stock development and high abundance in spring that partly compensated for the decline in summer. In contrast to the copepods, the cladocerans and, in particular, the rotifers displayed rather low annual mean abundance. In their main area of occurrence (Arkona Basin), their contribution to the stock decreased to only 12-17 % of their long term mean.

In autumn 2023, **macrozoobenthos** sampling was carried out at all eight stations along the German Baltic Sea coast, starting in the Kiel Bayand extending to the Bay of Mecklenburg, the Darss Sill, the Arkona Basin and the Pomeranian Bay. For most stations, a comprehensive dataset of autumn sampling since 1980 is available for long-term analysis.

The 138 species found in the macrozoobenthos in 2023 represent a relatively high diversity. The number of species found at the eight monitoring stations varied between 16 and 86. In general, neither a significant increase nor decrease in macrozoobenthos species number was observed in 2023. However, at some stations new observed species (never observed during the last 20 years at these stations) were found, e.g. *Philine punctata*. At all regions without exception, the oxygen supply in the bottom water in the current year was higher than 2 ml l^{-1}. Compared to the long-term mean, an average number of species was found at all stations. Only in the Bay of Kiel was an above-average diversity of 86 taxa found. Depending on the region, the abundances ranged from 331 ind. m^{-2} to 6775 ind. m^{-2} and the biomass (ash-free dry weight) from 1,8 g m^{-2} to 25,2 g m^{-2}.

Using the example of station K4 (Arkona Basin), we carried out a long-term analysis of the last 4 decades. The long-term development of species numbers, abundance and biomass is shown. To categorise the results, the oxygen and salinity values at the bottom over this period were also analysed and partially presented. Selected species (*Diastylis rathkei* and *Macoma balthica*) are used as examples to show what changes have taken place and what influence they may have on the ecosystem. For the second time (after 2021), the long-term data was used to calculate the Benthic Quality Index (BQI) and thus also the ecological status. Half of the stations were in 'good' status over the years. Three have always been assessed as 'poor' over the years, another one between 'poor' and 'good' status.

A total of 19 species on the German Red List (categories 1, 2, 3 and G) were observed at the eight monitoring stations. In addition to regularly encountered species such as *Arctica islandica* and species of the genus *Astarte*, somewhat less frequently observed taxa such as *Musculus discors*, *Aporrhais pespelecani*, *Tritia reticulata* and *Scalibregma inflatum* should also be emphasised here.

At 10, the number of invasive benthic species was relatively high in 2023. Most of them were already known from previous years. *Mya arenaria* and *Amphibalanus improvisus* have been common in the southern Baltic Sea for more than a hundred years. The amphipod *Grandidierella japonica* has been known from the southern Baltic Sea since 2016 and was also observed in the Bay of Kiel during the present study. The two polychaetes *Alitta succinea* and *Marenzelleria neglecta* have been regularly found during sampling in recent years. The bivalve *Ensis leei*, a North american species, was recorded for the first time on the Darss Sill (K8). It is normally (albeit sparsely) more common in the western part of the Baltic Sea. The Japanese cumacean *Nippoleucon hinumensis* has been widespread in the Baltic Sea since 2019. In addition to several detections that we have made in other campaigns in the German Baltic Sea (mainly in estuaries), we found it for the first time this year during monitoring sampling in the Kiel Bay (N3). Over the past ten years, we have found a total of 16 non-indigenous species (NIS) at our eight monitoring stations. The long-term trend over the last 10 years in arrivals was 0,8 NIS per year.

1 Introduction

This report presents the results of the biological monitoring conducted by the Leibniz-Institute for Baltic Sea Research in Warnemünde (IOW). Within Germany's Exclusive Economic Zone (EEZ), monitoring is undertaken on behalf of the Federal Maritime and Hydrographic Agency (BSH); in the Baltic Proper (Bornholm Basin, eastern Gotland Basin), long-term data collection is financed from the IOW's own budget.

The biological monitoring is one element of the international environmental monitoring programme of the Helsinki Commission (HELCOM) in which the IOW's predecessor institute had participated since its launch in 1979. Besides marine biology, the monitoring programme includes an extensive programme of hydrographic and chemical investigations (NAUMANN et al. 2024). The establishment of the IOW in 1992 assured the continuance of re-unified Germany's contribution to the HELCOM Monitoring Programme. International monitoring results are collected, discussed and published by HELCOM Periodic Assessments (HELCOM 1987, 1990, 1996, 2002) and Holistic Assessments (HELCOM, 2010, 2018, 2023a). Moreover, specialized Thematic Assessments are published, for example on the influence of climatic change (HELCOM 2013a), endangered species (HELCOM 2013b) and eutrophication (HELCOM 2014, HELCOM 2018). In a similar manner, short reports known as the 'Baltic Sea Environment Fact Sheets' (formerly 'Indicator Fact Sheets') are published annually (e.g. ÖBERG 2017, WASMUND et al. 2018a).

On a national level, the German Federal Government and the coastal states coordinate their measurements in the 'Bund/Länder-Arbeitsgemeinschaft Nord- und Ostsee' (BLANO). The collected data are transferred annually to ICES (International Council for the Exploration of the Sea, see https://www.ices.dk/data/Pages/default.aspx) via the national database MUDAB (https://geoportal.bafg.de/MUDABAnwendung/). One of the main tasks is the national coordination of the contributions to the EU's Marine Strategy Framework Directive (MSFD) (see www.meeresschutz.info/msrl.html). The MSFD (EUROPEAN UNION 2008; Directive 2008/56/EC) creates the regulatory framework for the necessary measures in all EU member states to achieve or maintain the 'good environmental status' in all European waters by actually 2020.

In order to determine the 'good environmental status', HELCOM relies on indicators (https://indicators.helcom.fi/filtering/). Members of the Biological Oceanography section of the IOW have been involved in the development or at least contributing to the following HELCOM 'core' and 'pre-core' indicators in connection with descriptors for biodiversity (D1), non-indigenous species (D2), food web (D4) or eutrophication (D5); see HELCOM (2013c, 2020):

- Zooplankton mean size and total stock (MSTS) (core)
- State of the soft-bottom macrofauna community (core), with Benthic Quality Index (BQI)
- Trends in arrival of new non-indigenous species (core)
- Chlorophyll-*a* (core)
- Diatom/Dinoflagellate Index (pre-core)
- Seasonal succession of dominating phytoplankton groups (pre-core)
- Cyanobacterial bloom Index (pre-core)

These indicators are applied on the international (HELCOM) and/or national level for the evaluation of the status of the marine environment. The monitoring data collected by IOW provide a solid basis to develop some of these indicators and to assess the state of the environment in the frame of the Marine Strategy Framework Directive. Close cooperation between oceanographers, marine biologists and marine chemists within IOW permits the comprehensive scientific analysis of the collected biological data which are interpreted in the light of the 2023 hydrographic-hydrochemical assessment of the Baltic Sea that has already been published (NAUMANN et al. 2024).

Dr. ANKE KREMP wrote the chapter on phytoplankton, including chlorophyll; Dr. JÖRG DUTZ wrote the chapter on zooplankton; Dr. MICHAEL L. ZETTLER wrote the chapter on macrozoobenthos.

2 Material and methods

2.1 Sampling strategy

The tasks undertaken by IOW in the monitoring programme are prescribed by the BSH (Bundesamt für Seeschifffahrt und Hydrographie), and they follow the HELCOM guidelines (https://helcom.fi/action-areas/monitoring-and-assessment/monitoring-guidelines/).
Biological monitoring by IOW includes determining the qualitative and quantitative composition of phytoplankton, mesozooplankton and macrozoobenthos, and determining the chlorophyll a content of water samples. The methods are set out in the HELCOM COMBINE manual (HELCOM 2017a). Fig. 1 shows the locations of the biological monitoring stations. They are labelled in accordance with the official nomenclature of the ICES Station Dictionary. If space is limited in figures and tables, the 'OMBMP' prefix is omitted in this report. The equivalents to the internal IOW station numbers are given in Table 1.

Five cruises represent different phases of the growth season and were conducted in February (EMB311: 04.02. - 16.02.2023), March (EMB314: 15.03. - 28.03.2023), May (EMB317: 03.05. - 15.05.2023), August (EMB323: 04.08. - 16.08.2023) and November (EMB328: 02.11. -14.11.2023).

Within the regular monitoring programme, plankton samples should be collected at two timepoints of each cruise at each station, if possible. There is a lag of about 7 to 12 days between sampling at a given station during outbound and inbound (return) journey. Thus, five cruises yield a maximum of 10 samples per station per year.

Phytoplankton sampling was performed at 5 stations located in the German EEZ. In addition, station K4 was included, representing the northern part of the Arkona Basin, but being located just beyond the border of the German EEZ in Danish waters. In 2023, stations were sampled only once for phytoplankton community analyses during each cruise. Chl *a* sampling followed the regular scheme i.e. including re-sampling of stations on the return track, except for March, when only one Chl *a* sample was taken at each station (Table 1, Table 2).

Zooplankton sampling was performed at 4 stations in the German Exclusive Economic Zone (EEZ) as well as at one station in Danish waters. Three stations were sampled during outward and return journeys on the scheduled cruises (Table 1). Due to a malfunctioning of the winch no samples could be obtained during the return journey on stations M1 and M2 in the Bay of Mecklenburg in February 2023, respectively.

Samples of the macrozoobenthos are usually taken once a year at eight stations (Fig. 1). In 2023, the samples were taken in November as usual (Table 1 and Table 4). All planned stations could be sampled.

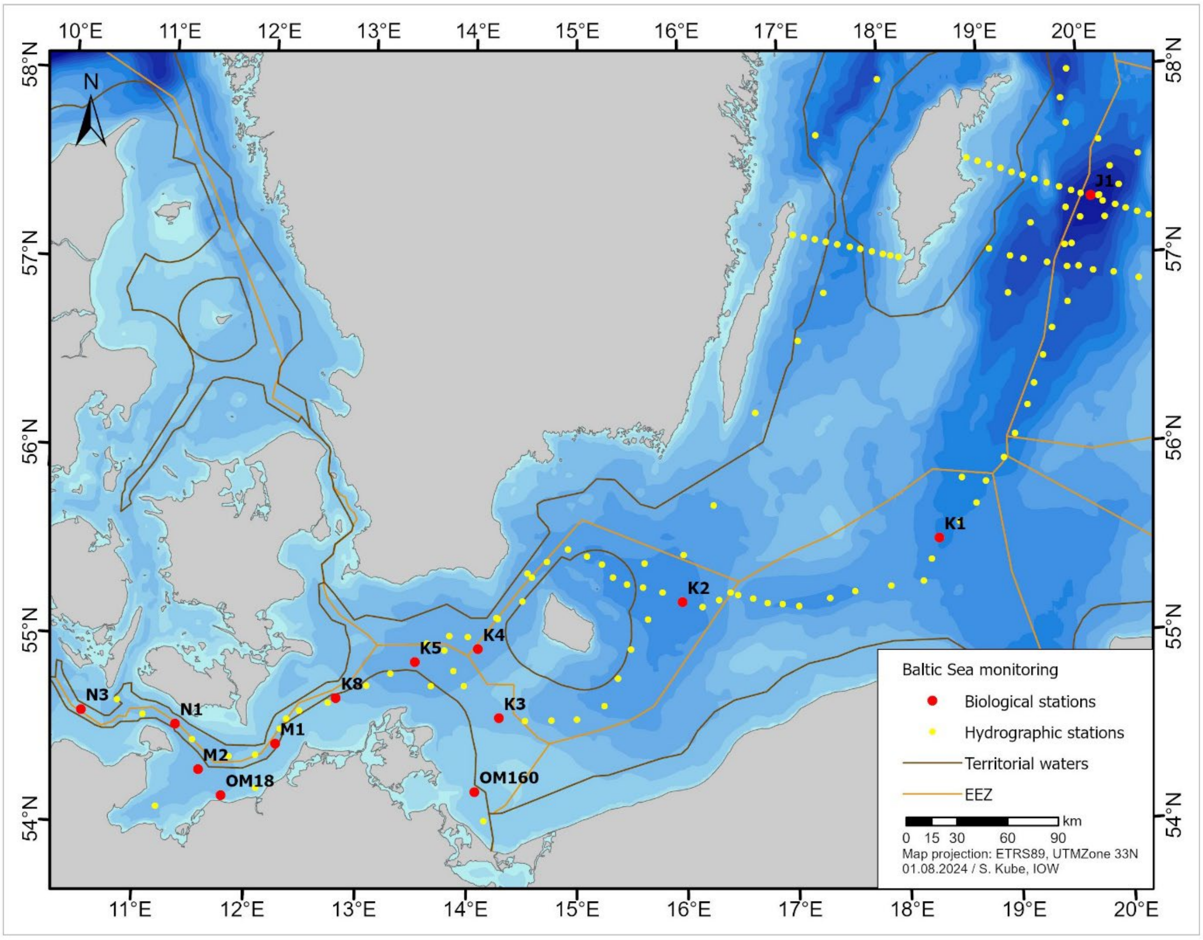


Fig. 1: Station grid for biological sampling in the Baltic Sea with depiction of the border of the Exclusive Economic Zone Germany (EEZ).

Table 1: Sampling statistics (number of sampling events) for the different parameters specified for regular monitoring stations in 2023 (Chl = Chlorophyll a, PP = Phytoplankton, ZP = Zooplankton; B = Benthos).

Station number	IOW-station no	Latitude	Longitude	Sea area	Chl	PP	ZP	B
Belt Sea								
N3	TF0360	54°36,0'N	10°27,0'E	Kiel Bay	5	5	5	1
N1	TF0010	54°33,1'N	11°19,2'E	Fehmarnbelt	-	-	-	1
M2	TF0012	54°18,9'N	11°33,0'E	Bay of Mecklenburg	10	5	9	1
OM18	TF0018	54°11,0'N	11°46,0'E	Bay of Mecklenburg	-	-	-	1
M1	TF0046	54°28,0'N	12°13,0'E	Bay of Mecklenburg	10	5	9	-
Arkona Basin								
K8	TF0030	54°43,4'N	12°47,0'E	Arkona Basin, west	9	5	-	1
K5	TF0113	54°55,5'N	13°30,0'E	Arkona Basin, central	9	5	10	-
K4	TF0109	55°00,0'N	14°05,0'E	Arkona Basin, east	5	5	5	1
Pomeranian Bay								
K3	TF0152	54°38,0'N	14°17,0'E	Pomeranian Bay	-	-	-	1
OM160	TF0160	54°14,4'N	14°04,1'E	Pomeranian Bay	-	-	-	1
Bornholm Basin								
K2	TF0213	55°15,0'N	15°59,0'E	Bornholm Basin	-	-	-	-
Gotland Basin								
K1	TF0259	55°33,0' N	18°24,0' E	Eastern Gotland Basin	-	-	-	-
J1	TF0271	57°19.2' N	20°02.8' E	Eastern Gotland Basin	-	-	-	-

2.2 Chlorophyll *a*

Samples for the determination of chlorophyll a (Chl *a*) concentrations were collected together with phytoplankton samples, at standard depths of 1, 5, 10, 15 m for a pooled sample and, occasionally, other depths, using a rosette water sampler. 200-500 ml of the pooled sample were filtered on glass-fibre filters (Whatman GF/F), which were flash-frozen in liquid nitrogen (-196 °C) and stored at -80 °C. In total, 49 chlorophyll samples were collected at 6 stations (Table 2). Ethanol (96 %) was used for the extraction, as specified by HELCOM (2017b). Chl *a* was determined according to WASMUND et al. (2011), Phaeopigments were not considered.

2.3 Phytoplankton

Sampling and analysis procedures followed HELCOM (2023b). Generally, two phytoplankton samples were taken at each station: A composite sample was mixed from equal parts of surface water from depths of 1 m, 2,5 m, 5 m, 7,5 m and 10 m. In addition, one sample was taken from below the upper pycnocline (usually from a depth of 20 m). If distinctive fluorescence maxima were present in deeper layers, additional samples were taken from that depth. The water samples (200 ml) were fixed with 1 ml of acid Lugol's solution and stored until analysis (up to 6 months). In total, 30 phytoplankton samples were collected at 6 stations (Table 2).

Table 2: Phytoplankton data representation in 2023 for different cruises and sampling stations. (X: one sample taken per cruise, XX two samples taken per cruise with app. 10 days in between), geographical locations see Fig. 1.

Station number	IOW-station number	EMB311 04.02.-16.02.		EMB314 15.03.-28.03.		EMB317 03.05.-15.05.		EMB323 04.08.-16.08.		EMB328 02.11.-14.11.	
		Phyto	Chl *a*	Phyto	Chl *a*	Phyto	Chl *a*	Phyto *	Chl *a*	Phyto	Chl *a*
Belt Sea											
N3	TF0360	X	X	X	X	X	X	X	X	X	X
M2	TF0012	X	XX	X	XX	X	XX	X	XX	X	XX
M1	TF0046	X	XX	X	XX	X	XX	X	XX	X	XX
Arkona Basin											
K8	TF0030	X	XX	X	XX	X	XX	X	XX	X	XX
K5	TF0113	X	XX	X	XX	X	XX	X	XX	X	X
K4	TF0109	X	X	X	X	X	X	X	X	X	X

Phytoplankton biomass was analysed based on cell concentrations of individual species determined microscopically using the standard method of UTERMÖHL (1958). Individuals were assigned to size classes according HELCOM guidelines (OLENINA et al. 2006; HELCOM 2017c). For the most abundant species at least 50 individuals per sample were counted. All in all at least 500 individuals were counted per sample to reduce the statisticall error to < 10 %. Cell concentrations of each species and size classes were multiplied by specific biovolumes of identified species and respective size classes. Assuming a density of 1 g cm^3 the figure of biovolume equates to the biomass (wet weight).

Counting, calculation and data output were facilitated by the software "OrgaCount" (AquaEcology Oldenburg), based on the biovolume files of the HELCOM Phytoplankton Expert Group (PEG). All samples taken in 2023 were counted based on the ICES and HELCOM biovolume file PEG_BIOVOL2022 (https://www.ices.dk/data/Documents/ENV/PEG_BVOL.zip).

2.4 Mesozooplankton

Zooplankton sampling followed the recommendations of the HELCOM COMBINE manual (HELCOM 2021). Vertical net tows were conducted with a Work-Party 2 net (WP-2) of 100 µm mesh size. The net was equipped with an operating/closing mechanism released by a drop messenger and a T.S.K Flowmeter (Tsurumi-Seiko Co. Ltd., Yokohama, Japan) for the measurement of the filtrated water. The net was operated with a hauling speed of 0,5 m s^{-1}. In the case of a well-mixed water column, a single net catch was conducted from two meters above the sea floor to the surface. In case a deep halocline that formed through saline inflows or a shallower thermocline caused by seasonal warming, separate hauls were taken in the respective water layers. Net angles greater than 25° were avoided during sampling by adding sufficient weight to the cod end of the net (> 40 kg). The samples were preserved in Borax-buffered, 4 % aqueous formaldehyde solution and stored at cool/dark conditions until their processing in the laboratory. In total, 52 zooplankton samples were collected at 5 stations. Table 3 provides the details about the timing and specific depth layers that were sampled over the season at the respective monitoring stations.

Table 3: Sample statistics of zooplankton hauls on monitoring cruises from February to November 2023. For geographical location see Fig. 1.

Station OMBMP-	**EMB311** **TF-02-2023** **04.02. - 16.02.** Depth (m) from – to	**EMB314** **TF-03-2023** **15.03. - 28.03.** Depth (m) from - to	**EMB317** **TF-05-2023** **03.05. - 15.05.** Depth (m) from - to	**EMB323** **TF-08-2023** **04.08. - 16.08.** Depth (m) from - to	**EMB328** **TF-11-2023** **02.11. - 14.11.** Depth (m) from – to
N3	15 – 0	15 – 0	15 – 0	15 – 0	16 – 8 – 0
M2	20 – 0	24 – 0 22 – 9 – 0	19 – 0 18 – 0	19 – 10 – 0 22 – 0	22 – 11 – 0 22 – 8 – 0
M1	24 – 9 – 0	27 – 0 25 – 0	22 – 0 26 – 0	25 – 0 26 – 0	26 – 15 – 0 26 – 0
K5	43 – 33 – 0 43 – 32 – 0	45 – 0 44 – 0	42 – 0 41 – 0	44 – 0 44 – 0	41 – 26 – 0 45 – 24 – 0
K4	44 – 32 – 0	47 – 38 – 0	46 – 36 – 0	45 – 0	46 – 0

The analysis of samples followed the established HELCOM guidelines (HELCOM 2021). In short, a minimum number of individuals was identified and counted microscopically in a Bogorov chamber. Several subsamples from the total sample were analysed. With the exception of nauplii and tintinnids, at least 100 individuals from three taxa were counted. The abundance (ind. m^{-3}) was calculated from the counts and the volume of seawater filtered by the net. The identification of zooplankton species followed an internal IOW species list summarizing the long-term record in the western Baltic Sea, the “Zooplankton Atlas of the Baltic Sea” (Telesh et al. 2008, 2009) and the species list of the HELCOM EG Zoo working group. The taxonomic classification in this report is based on the World Register of Marine Species (WoRMS 2024). In the case of *Bosmina* spp. and *Synchaeta* spp., identification to the species level is unresolved; their abundances were recorded and reported on the level of the genus. In line with the standards of the Integrated Taxonomic Information System (ITIS 2024), marine Bryozoa were listed as Gymnolaemata. The databases of the information system on Aquatic Non-Indigenous Species (AquaNIS 2024) and of the European Network on Invasive Species (NOBANIS 2024) served as references for the classification of invasive species. The biomass was calculated as wet weight by using conversion factors from the species list of the HELCOM EG Zoo working group.

2.5 Macrozoobenthos

In November 2023, benthos investigations were undertaken at eight stations from the Kiel Bay to the Pomeranian Bay (Table 4 and Fig. 1). One type of Van Veen grab samplers was deployed (about 1000 cm², weighing 70 kg). Three hauls were taken at each station. Each haul was rinsed in seawater through a 1 mm mesh sieve. The sieve residue was transferred to beakers and fixed in 4 % buffered formalin (HELCOM 2017a). Additionally, at all stations sampled, a “Kieler Kinderwagen” botanical dredge with a 1 m rectangular mouth and a mesh size of 5 mm was deployed. Especially in relation to vagile and rarer species, the dredge yielded finds that would be missed with the grab alone.

Further processing of samples was undertaken in the laboratory. After rinsing each haul, taxa were sorted under a binocular microscope at 10 - 20 x magnification and, except for a few groups (e.g., Nemertea, Halacaridae), were determined to species level. As far as possible, nomenclature complied with the ‘World Register of Marine Species (WoRMS)’. Abundance and biomass (expressed as ash free dry weight, afdw, throughout the whole report) were also recorded. To ensure comparability of weight determinations, HELCOM guidelines were followed (HELCOM 2017a), and samples were stored for three months before processing. Wet, dry, and ash-free dry weights were measured on a microbalance. The whole procedure of sorting and analysis follows the standard operating procedure (SOP) of the accredited benthos analytical laboratory of the IOW.

Table 4: Station list of macrozoobenthic investigations in November 2023.

HELCOM-ID	IOW-ID	date	depth	north	east	sea area
N3	360	03.11.2023	18.8	54° 36.00	10° 27.00	Kiel Bay
N1	010	03.11.2023	26.0	54° 33.20	11° 20.00	Fehmarnbelt
M2	012	02.11.2023	25.1	54° 18.90	11° 33.00	Mecklenburg Bay
OM18	018	02.11.2023	20.8	54° 11.00	11° 46.00	Mecklenburg Bay, south
K8	030	04.11.2023	23.6	54° 44.00	12° 47.40	Darss Sill
K4	109	13.11.2023	46.1	55° 00.00	14° 05.00	Arkona Basin
K3	152	05.11.2023	28.6	54° 38.00	14° 17.00	Pomeranian Bay, north
OM160	160	05.11.2023	11.4	54° 14.50	14° 04.00	Pomeranian Bay, central

2.6 Quality assurance (QA)

Chlorophyll *a*

As an internal quality assurance measure, every tenth chlorophyll sample was taken twice and analysed separately to test parallel deviations. The results were entered into the range control chart. The fluorometer was calibrated every six months. As an external quality assurance measure, IOW regularly participates in chlorophyll comparisons within QUASIMEME AQ-11 (chlorophyll in seawater). The rounds 2023.1 and 2023.2 were passed with very good results.

Phytoplankton

For phytoplankton quality assurance as implemented by HELCOM PEG, two abundant species were counted twice from every tenth sample, and replicate results were entered into the range control chart. PEG runs annual training courses and undertakes regular ring tests, in which IOW participates.

Mesozooplankton

The quality assurance followed the protocol for internal quality control concerning documentation and analyses provided by HELCOM (2021). This includes a duplicate analysis of every 20th zooplankton sample as an intra-laboratory routine to check the reliability of the zooplankton analysis. In addition, the validity of counting results and assessment of their accuracy was tested. Deviations of repeated analyses were well below the threshold value for critical errors (variation coefficient < 1 %). Individual operator and within-laboratory precision were low (variation coefficient 2,0 – 3,2 %). Data stored in databases was quality-checked and validated.

Macrozoobenthos

The IOW macrozoobenthos working group has participated in all QA measures to date. The results of the latest ring test from spring 2018, presented by the Umweltbundesamt (UBA) in March 2019, confirmed the high quality of the macrozoobenthos analyses. Internal double checks of four samples of the 2023 monitoring season confirmed high accuracy. In addition, internal and external audits of our analysis groups were successfully passed. In 2022 we received the re-accreditation by DAkkS (Deutsche Akkreditierungsstelle).

3 Abiotic conditions in 2023

A detailed description of the hydrographic-hydrochemical conditions in the western and central Baltic Sea in 2023 is given in NAUMANN et al. (2024). This chapter summarizes the conditions in the study area for the biological investigations in the south-western Baltic Sea.

Inflow events and salinity

The series of years from 2017 to 2022 which were characterised by weak salt water inflow activity into the Baltic Sea was interrupted in 2023. The seasonal salinity distribution in 2023 was mainly controlled by the minor barotropic inflow in December 2022 and the baroclinic inflows in late summer to autumn 2023. During December 2023 intensified inflow activity was recorded, which was classified as midsized Major Baltic Inflow (MBI) event after MOHRHOLZ (2018) and imported a salt mass of 1,7 Gt (salinity >15 g kg^{-1}) into the deep water of the Arkona Basin.

At the MARNET monitoring platform "Darss Sill" salinity ranged from 9,7±1,6 g kg^{-1} at 7 m depth and 13,4±3,6 g kg^{-1} at 19 m throughout the year 2023. The deeper sensors capture near-bottom salinity variability, thus serving as sensitive indicators of inflow activity. Unlike the annual means of 2016 (15,6 ± 3,5 g kg^{-1}) and 2014 (14,9 ± 3,4 g kg^{-1}), which both experienced strong inflow events, the year 2023 still exhibited above-average mean salinity and increased variability at the near-bottom, suggesting moderate inflow activity in 2023. The bottom water of the Arkona Basin was still heavily influenced by the inflow event from late December 2022 during the first two weeks of 2023. Peak salinities in the bottom layers reached 22 g kg^{-1}. By the end of April, the bottom salinity was decreased to a minimum of 9 g kg^{-1}. In early May, a new influx of water reached Arkona Basin, characterized by salinity levels around 16 g kg^{-1}. Towards the end of July, a weak baroclinic inflow at Darss Sill began to replenish the salt pool in the Arkona Basin. By mid-August, a second baroclinic inflow had established a quasi-steady state of 17 g kg^{-1} in bottom salinity which was slightly lower than the 19 g kg^{-1} observed at Darss Sill. In December, the water column, previously nearly well-mixed, became stratified again due to a barotropic inflow, causing bottom salinity to rise sharply to peak values of 20 g kg^{-1}.

Oxygen

The oxygen concentration in surface water is in general controlled by the seasonal changing temperature and primary production. Physical processes like mixing and upwelling can intermediately cause a deviating oxygen concentration. In 2023, the highest average oxygen concentrations measured during the monitoring campaigns in surface waters of the western Baltic Sea were observed in February, March and May and ranged between about 8 ml l^{-1} and 9 ml l^{-1} oxygen. The maxima in the western Baltic Sea were mostly measured in March, as this month usually shows the lowest water temperature. Spring bloom started earlier in these areas due to positive air temperature anomalies from January to March 2023 of 2,5-1,2 K. In the Bornholm Sea the later spring bloom shifted the maxima to May. After the summer minimum in August (about 6 ml l^{-1}), subsequent cooling and enhanced input of atmospheric oxygen in autumn increased the oxygen concentration of surface water to about 7 ml l^{-1} oxygen in November. In the bottom water, the partly cool and stormy weather in summer 2023 as well as minor barotropic inflow event of December 2022 resulted in a consistently good oxygen supply from the Belt Sea to the Arkona Sea (> 2 ml l^{-1} in summer to 7 ml l^{-1}).

Temperature

The winter of 2022/2023 continued a series of warm winters compared with the 30 years reference period 1991-2020. Thus, the sea surface cooling of the Baltic Sea was weaker compared to the reference period. Considering especially the study area for the biological investigations in the western Baltic Sea, the SST ranged between 4 °C at the Darss Sill and 5 °C in the central Bornholm Basin in February 2023. Thus, the climatological mean of 2,5 °C was exceeded by 2,5 K. No surface temperature stratification was observed in February 2023. A warm halocline water layer of about 10,0 °C originating from a baroclinic inflow of summer 2022, spread along the thalweg to the eastern Bornholm Basin. At the same time, the bottom layer in the eastern Arkona Basin and in the western Bornholm Basin was covered with cool water of about 6,0 °C originating from a minor barotropic inflow event in December 2022. In March 2023 the SST in the Baltic Sea was with 3,8 °C to 4,0 °C from the Danish straits to the Arkona Basin slightly less than in February but still about 1,5 K above the climatological mean. The upper layer was well mixed down to the halocline. The warmer bottom water found in the Arkona Basin in February, was completely replaced by cold water from winter inflows in March. In May 2023 the seasonal thermocline was established throughout the Thalweg transect of the western Baltic Sea. The sea surface temperatures ranged from 11,9 °C in the Kiel Bight to 9,1 °C in the Arkona Basin. This was 2 to 3 K above the climatological mean values for the western Baltic. From the Danish Straits to the Arkona Basin the thermocline depth was at 15 m to 20 m. Below this thermocline the cold winter water has had a core temperature of 4,5 °C in the Bornholm Basin. Below the intermediate layer the temperatures increased with depth. The bottom water temperature in the Bornholm Basin was about 8,6 °C in May 2023. In August 2023, the surface temperature in the Baltic Sea reached its annual maximum. The typical summer thermal stratification developed throughout the Baltic Sea. The seasonal thermocline was found at depths of about 20 m in the western Baltic Sea. In the Fehmarn Belt and the Arkona Basin the surface temperature reached 18,5 °C. The SST in the Bornholm Basin was about 1,5 K below the long-term mean. Below the thermocline warm baroclinic summer inflows had replaced the former cool bottom water in the Arkona Basin. Maximum bottom water temperature ranged between 16,5 °C in the Arkona Basin and 12,1 °C in the Bornholm Basin. The general temperature distribution in November 2023 reflected the autumnal cooling and the erosion of the seasonal thermocline in the surface layer. From the Fehmarn Belt to Darss Sill surface temperatures were about 11,5 °C. Except a slightly cooler region in the western Bornholm Basin the SST in the central Baltic Sea was at 10 °C, which was about 2 K higher than normal. From the Belt Sea to the Arkona Basin the bottom water was significantly warmer than the surface water layer. The bottom layer of the Arkona Basin showed a maximum deep-water temperature of 14,6 °C. The halocline layer in the Bornholm Basin had a core temperature of 11,6 °C.

Inorganic nutrients

The concentration of inorganic nutrients in the water column was measured on the Thalweg transect between the Mecklenburg Bight and the western Gotland Sea during all cruises in 2023.

Considering the winter (February) nutrient data as reservoir for the phytoplankton of the year, neither nitrate nor phosphate data showed a significant trend in surface waters of the western Baltic Sea during the last decade. Inter- and intraannual variations of nutrient concentrations are quite high in the shallow water due to mixing, upwelling and nutrient load from rivers. Nitrate surface concentrations ranged between 2,8 µmol l^{-1} (2019) and 5,8 µmol l^{-1} (2013, 2022) in February in Mecklenburg Bight. Phosphate surface concentrations ranged between 0,6 µmol l^{-1} (2014, 2017) and 0,9 µmol l^{-1} (2013) in February in Mecklenburg Bight between 2013 and 2022. In 2023, the February surface concentrations of nitrate and phosphate were 5,5 µmol l^{-1} and 0,7 µmol l^{-1} respectively in Mecklenburg Bight and thus within the decadal range.

In February 2023, the phosphate concentration ranged from 0,7 µmol l^{-1} in the Mecklenburg Bight to 0,5 µmol l^{-1} in the Arkona Sea in the surface mixed layer. A phosphate maximum of 2,3 µmol l^{-1} at about 10 m above the sea floor was visible in the Bornholm Sea. The nitrate concentration in surface water decreased from 5,5 µmol l^{-1} in the Mecklenburg Bight to < 3 µmol l^{-1} in the Arkona Basin. Relatively high nitrate concentrations were determined in the deep water of the Bornholm Basin and the southern Baltic Sea of about 8 µmol l^{-1}. In March, phosphate was mostly consumed in the Mecklenburg Bight and partly declined in the Arkona Sea and Bornholm Sea surface water. The concentration distribution of nitrate reflected consumption in the western Baltic Sea surface water. The measured range was from the detection limit in the Mecklenburg Bight to between 1 µmol l^{-1} and 2 µmol l^{-1} in the Arkona and Bornholm Seas. In May, surface water showed a low phosphate concentration in the range of 0,05 µmol l^{-1} to 0,2 µmol l^{-1} until 40 m depth. Nitrate was depleted to below the detection limit in surface water. The oxygenated Bornholm Sea showed a maximum nitrate concentration of 10,2 µmol l^{-1}. In August surface water phosphate still scattered around 0,05 µmol l^{-1}. The nitrate concentration had declined in August in most water bodies of the Thalweg transect to below the detection limit. Only in the deep water of the Bornholm Sea and the southern Baltic Sea concentrations above 3 µmol l^{-1} nitrate were measured. In November, the consumption of nitrate and phosphate concentrations in previous months were partly replenished in surface water.

The surface water DIN/DIP ratio (sum of ammonium, nitrate, and nitrite concentrations versus the phosphate concentration) ranged between about 9 mol mol^{-1} and 5 mol mol^{-1} from the Belt Sea to the Bornholm Sea in February 2023. The N/P ratio showed a decreasing trend from west to east: Belt Sea 9,2 mol mol^{-1}, Mecklenburg Bight 8,7 mol mol^{-1}, Arkona Sea 6,9 mol mol^{-1}, Bornholm Sea 5,5 mol mol^{-1}. The distribution pattern is similar to the situation in the previous year and confirmed again that nitrogen was a limiting factor in the Baltic Proper, giving diazotrophic cyanobacteria an advantage compared to primary producers that depend on nitrate.

4 Results and discussion

4.1 Phytoplankton and chlorophyll *a*

4.1.1 Spatial patterns of phytoplankton community composition and seasonal succession

Kiel Bay (N3, Belt Sea)

In the southernmost part of the study area in the Belt Sea, represented by Station N3 in the Kiel Bight, phytoplankton production had already started by the time of the February monitoring cruise. Chl *a* values of 2,9 µg l^{-1} indicate significant phytoplankton growth. Total phytoplankton biomass at that time already amounted to 362 µg l^{-1} here (Fig. 2). In February, phytoplankton in Kiel Bight was dominated by diatoms, specifically *Rhizololenia spp.*, which constituted 72 % of total phytoplankton biomass, followed by dinoflagellates (16 %) and cryptophytes (5 %). By March, the phytoplankton spring bloom was fully developed in Kiel Bight. Annual peak concentrations of Chl *a* amounted to 12,8 µg l^{-1}, and biomass concentrations had increased more than 10-fold within just a few weeks, to the annual maximum of 4636 µg l^{-1}. As in February, also in March high diatom biomasses were produced by blooming *Rhizosolenia* spp. By May, annual minimum Chl *a* concentrations of 1,7 µg l^{-1} and a low phytoplankton biomass of only 76,8 µg l^{-1} indicated that the diatom spring bloom had declined in the Kiel Bight. The May phytoplankton community was dominated by diverse taxa, the dinoflagellate *Heterocapsa rotundata* and cryptophytes being most abundant, as typical for an intermediate succession stage. In August, Chl *a* concentrations of 2 µg l^{-1} were only slightly higher than in May in the Kiel Bight and biomass was mainly produced by diatoms, specifically *Proboscia alata*, and *Pseudosolenia calcar-avis,* and dinoflagellates of Gymnodiniales as well as potentially toxic *Prorocentrum micans*. By the time of the November monitoring cruise, Chl *a* concentrations had increased again compared to August, now amounting to 4,4 µg l^{-1} and representing the second highest Chl *a* concentration of the annual cycle in the Kiel Bight. This pattern likely reflects the high diatom representation (71 %) in the most marine community of the study area, which at the time of sampling was dominated by *Ditylum brightwellii*, *Pseudosolenia calcar-avis* and *Thalassiosira* sp.. In recent years, such high diatom biomasses at the end of the phytoplankton production cycle have increasingly been observed.

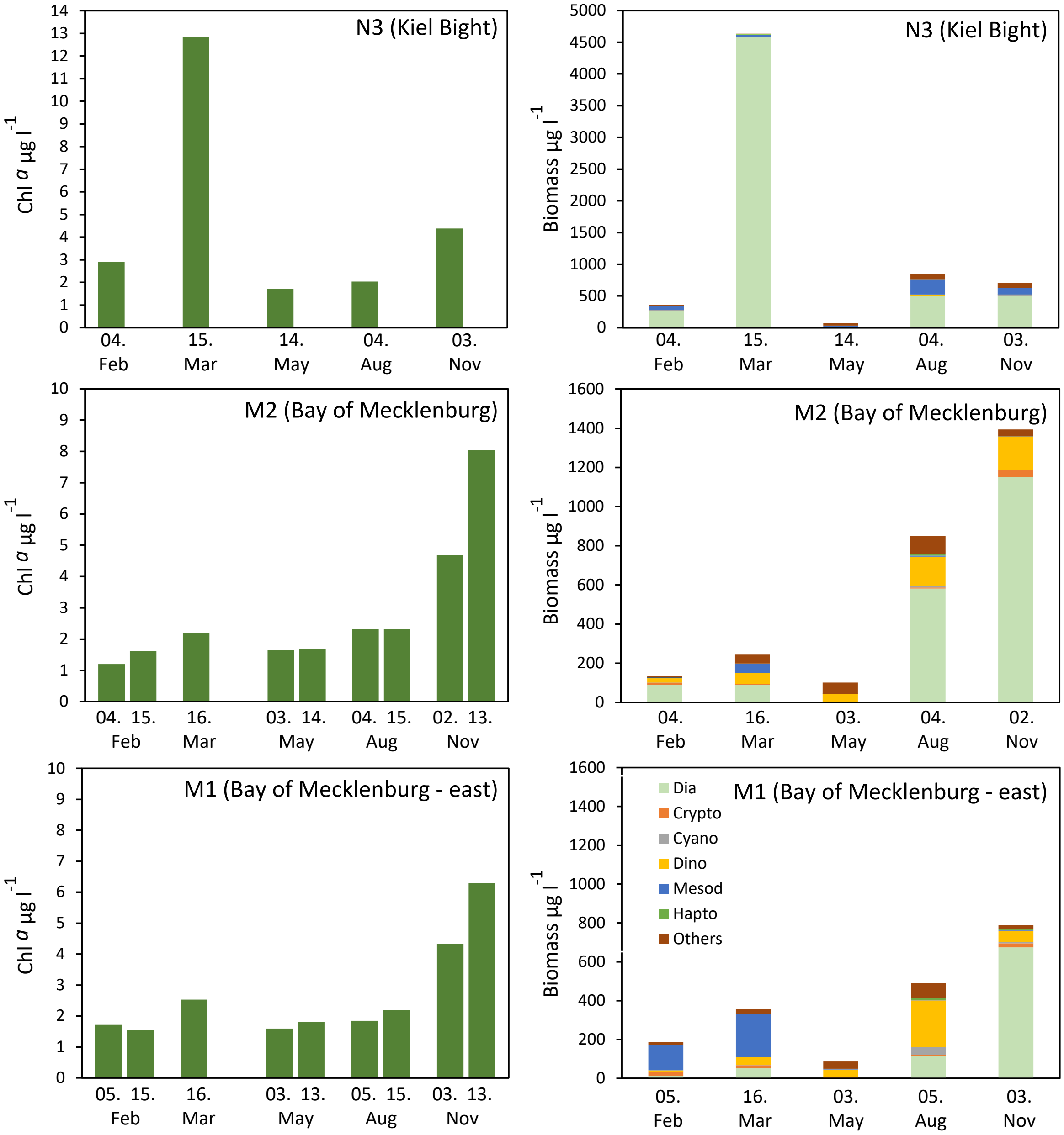


Fig. 2: Seasonal succession of Chl a *(left column) and biomass composition (right column) at the sampling stations N3, M2 and M1 in the Belt Sea and Bay of Mecklenburg in 2023.*

Bay of Mecklenburg (M2, M1, Belt Sea)

Seasonal succession patterns of Chl *a* at the two Bay of Mecklenburg stations were nearly identical (Fig. 2). Like in the Kiel Bight, the spring bloom was already ongoing in February, although Chl *a* concentrations of 1,2 µg l^{-1} and 1,7 µg l^{-1}, respectively, were still quite low at that time compared to Kiel Bight. Phytoplankton biomass was dominated by diatoms of *Rhizosolenia delicatula* and *Thalassiosira* at the more southern station M2, constituting › 40 % of the biomass. The community at station M1, further north, was entirely different, being dominated by the kleptoplast containing ciliate *Mesodinium rubrum* (70 % of the biomass) and its cryptophyte prey, *Teleaulax*. As in Kiel Bight, the annual measured peak of the spring bloom in the Bay of

Mecklenburg occurred in March. Here, too, the respective Chl *a* levels of 2,2 µg l^{-1} and 2,5 µg l^{-1} remained far below the ones encountered in Kiel Bight at the same time. As in February, biomass at M2 was equally shared by diatoms, with *Rhizosolenia delicatula* being the most prominent species; in March it was dinoflagellates and *M. rubrum*. At M1, like in February, *M. rubrum* dominated the biomass almost entirely, making a nearly 70 % share here. By May, the spring bloom was nearly over in the Bay of Mecklenburg, when Chl *a* concentrations had declined to 1,5 µg l^{-1} and 1,6 µg l^{-1} at stations M2 and M1 and Phytoplankton biomass was at its annual measured minimum (101,8 µg l^{-1} and 86,6 µg l^{-1}). At both Bay of Mecklenburg stations, the small peridinoid dinoflagellate *Heterocapsa rotundata* had high biomass shares of 30 % in an otherwise heterogeneous community. In August phytoplankton Chl *a* levels had increased slightly again in the Bay of Mecklenburg to concentrations of 1,8 µg l^{-1} – 2,8 µg l^{-1}. Total biomass had increased to 850 µg l^{-1} at station M2 and 489 µg l^{-1} at M1. The summer community in August was dominated by diatoms in the western Bay of Mecklenburg (M2), while dinoflagellates and cyanobacteria became more prominent in the eastern Bay of Mecklenburg (M1), where dinoflagellates had biomass shares up to 50 % - *Polykrikos schwartzii* and *Tripos muelleri* being abundant taxa. *Aphanizomenon,* representing the brackish Baltic proper*,* contributed 5 % to biomass of the community here. Alltogether cyanobacteria had a biomass share of 8 % at M1, the easternmost station of the Belt Sea, representing the transition to low salinity waters of the Baltic Proper. Late autumn as represented by the November cruise was apparently the most productive period of the annual phytoplankton cycle in the Bay of Mecklenburg, as captured by the 2023 monitoring campaign. Annual peak Chl *a* and biomass concentrations were measured here, ranging from a Chl *a* minimum of 4,3 µg l^{-1} at Station M1 to a maximum of 8 µg l^{-1} on the return journey at station M2. Corresponding maximum biomasses ranged from 789 µg l^{-1} at M1 to 1390 µg l^{-1} at station M2. As in August, biomass in November was largely dominated by diatoms, making 85 % and 82 % of biomass at station M1 and M2 respectively. The community was dominated by diatoms with *Cerataulina bergonii* and contributing 67 and 65 % here respectively. *Rhizosolenia fragilissima* and centric diatoms, as well as *M. rubrum* constituted much of the remaining biomass.

Arkona Basin (K5, K4, Baltic Proper)

In Arkona Basin, the phytoplankton spring bloom had begun at all three monitoring stations in February (Fig. 3). Chl *a* concentrations ranged from 1,68 µg l^{-1} at southernmost station K8 to 1,41 µg l^{-1} at station K4 in the north of the basin, reflecting the typical progression of the spring bloom from south towards the northern basins. Increasing Chl *a* concentrations measured on the return journey south (2,1 µg l^{-1} at K8 to 2,2 µg l^{-1} at K5; K4 not measured) several days later indicate that the spring bloom was developing. Measured Chl *a* concentrations in February corresponded to total phytoplankton biomasses of 621,5 µg l^{-1} at K8 in the south and 82,4 µg l^{-1} at K5 in central Arkona Basin, to 52,6 µg l^{-1} at station K4 in the north (Fig. 3). Phytoplankton biomass in Arkona Basin in February was dominated by *M. rubrum* at all 3 stations, contributing 86,8 µg l^{-1} of total phytoplankton biomass at southernmost K8, 65,6 µg l^{-1}at K5, in central Arkona Basin and 48,5 µg l^{-1} at northernmost K4. High biomasses of *M. rubrum* were accompanied by corresponding biomasses of *Teleaulax*, the cryptophyte prey of *M. rubrum*. In March Chl *a* concentrations had increased at all Arkona Basin stations, now ranging from 2,4 µg l^{-1} at stations K8 to 3 µg l^{-1} at K5 and 1,6 µg l^{-1} at K4 in eastern Arkona Basin. Corresponding phytoplankton biomasses were between 166,1 µg l^{-1} at K8, 355,6 µg l^{-1} at K5 and 234,8 µg l^{-1} at K4. Total phytoplankton biomasses in March were significantly lower compared to February at K8, but were still dominated by *M. rubrum*, as were biomasses at K5 and K4 (Fig. 3). The ciliate now co-occurred with diatoms of *Thalassiosira* and *Skeletonema marinoi*. Generally, the eastward/northward delay in progression of the spring bloom was well reflected by the Chl *a* and biomass succession patterns. Highest spring biomass levels were detected at the eastern stations K5 and K4 in March. At the time of the monitoring cruise in May, Chl *a* concentrations had decreased compared to March, to 1,7 µg l^{-1} at K8 in the western Arkona Basin, and 1,4 µg l^{-1} and 1,1 µg l^{-1} at K5 and K4, respectively, in central and eastern Arkona Basin, indicating that the annual spring bloom was ending. Phytoplankton biomasses had declined correspondingly to 71,5 µg l^{-1} at station K8, to 157,9 µg l^{-1} at K5 and to 132,8 µg l^{-1} at K4. Biomass was generally dominated by dinoflagellates, specifically *Heterocapsa rotundata* and Gymnodiniales, constituting 45 % of the May phytoplankton biomass at station K8. *Mesodinium rubrum* prevailed at station K5 in May, but was nearly absent from the other two Arkona stations. Potentially toxic Prymnesiophytes had significant biomass shares of 34 % at the northernmost Arkona station K4. The summer community in Arkona Basin, sampled in August, was characterized by intermediate Chl *a* concentrations ranging from 1,7 µg l^{-1} to 2,4 µg l^{-1}. Apparently the summer bloom was already declining at the time of the cruise in August, as Chl *a* concentrations on the return journey were generally lower than on the outward journey eastwards. Chl *a* concentrations corresponded to total biomasses of 934,7 µg l^{-1} at K8 in western Arkona Basin, to 755,1 µg l^{-1} at K5 in central, and to 371,2 µg l^{-1} at K4 in eastern Arkona Basin, decreasing successively towards the east. At the westernmost station K8, and the central K5, diatoms generally dominated the biomass in August (42,2 % at K8 and 20,7 % at K5) with *Rhizosolenia fragilisima* being the most important species in terms of biomass. At K5 cyanobacteria contributed 22,1 % of biomass (*Nodularia spumigena* 15,7 % and *Aphanizomenon* 5 %). The summer community at K4 in the eastern Arkona Basin had a different character, with a diverse dinoflagellate community contributing high biomass shares (29,49 %) and diatoms being less prominent. Typical diazotrophic cyanobacteria, *Nodularia spumigena* and *Aphanizomenon* were also present here, though at lower biomasse shares compared to K5. By November, inorganic nutrients were partially replenished (see chapter 3) and generally supported high Chl *a* (6,3 µg l^{-1} at K5 and 3,6 µg l^{-1} at K4) and phytoplankton biomass concentrations at sampled stations (1168 µg l^{-1} at K5 and 228,5 µg l^{-1} at K4, K8 not sampled) in Arkona Basin (Fig. 3). Biomass at both station, K5 in central and K4 in eastern Arkona Basin, was dominated by diatoms, mainly represented by *Cerataulina bergonii* and *Rhizosolenia fragilissima.* At station K4 in the eastern Arkona Basin *Teleaulax* and *Mesodinium rubrum* additionally contributed significant shares of biomass.

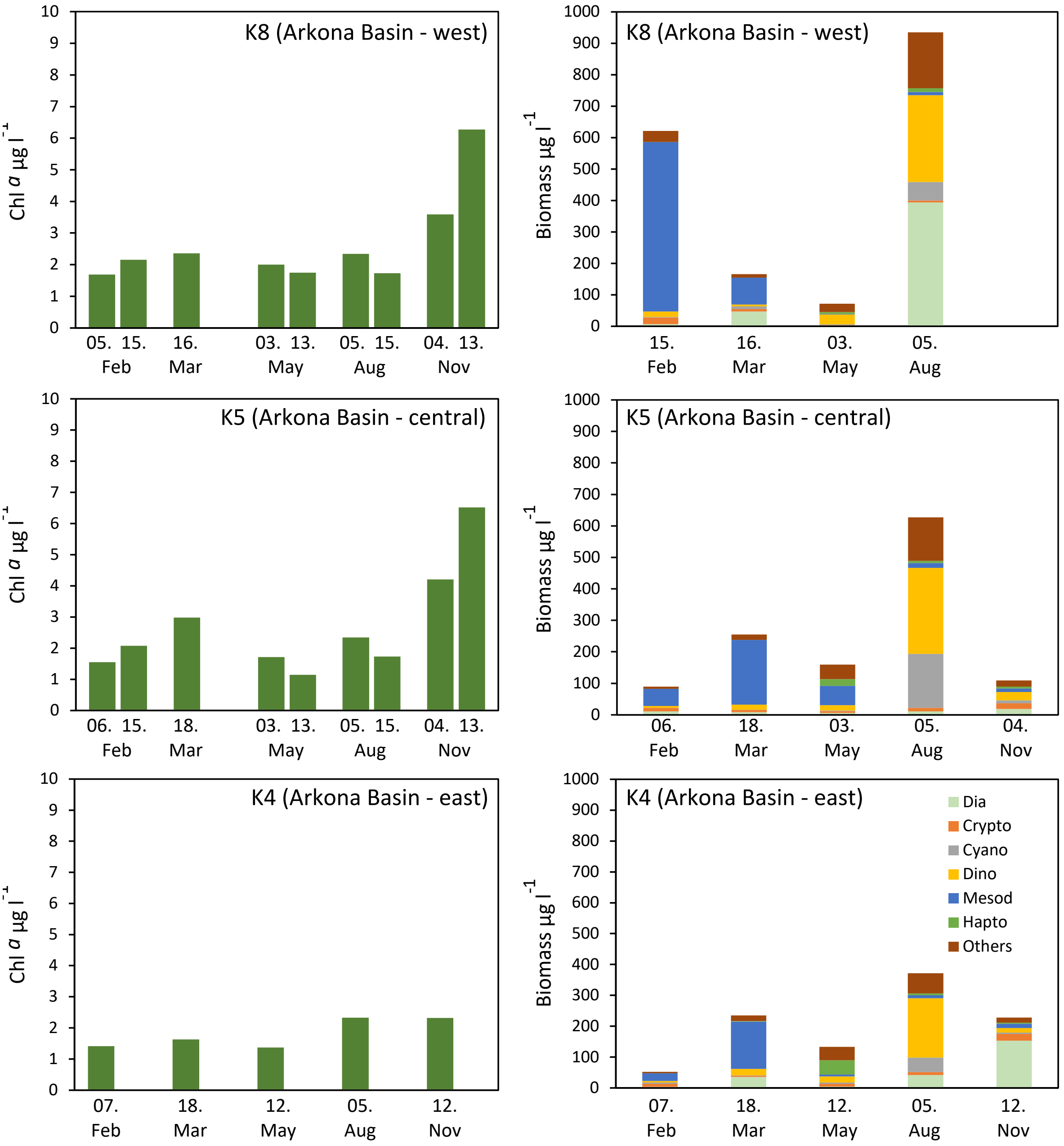


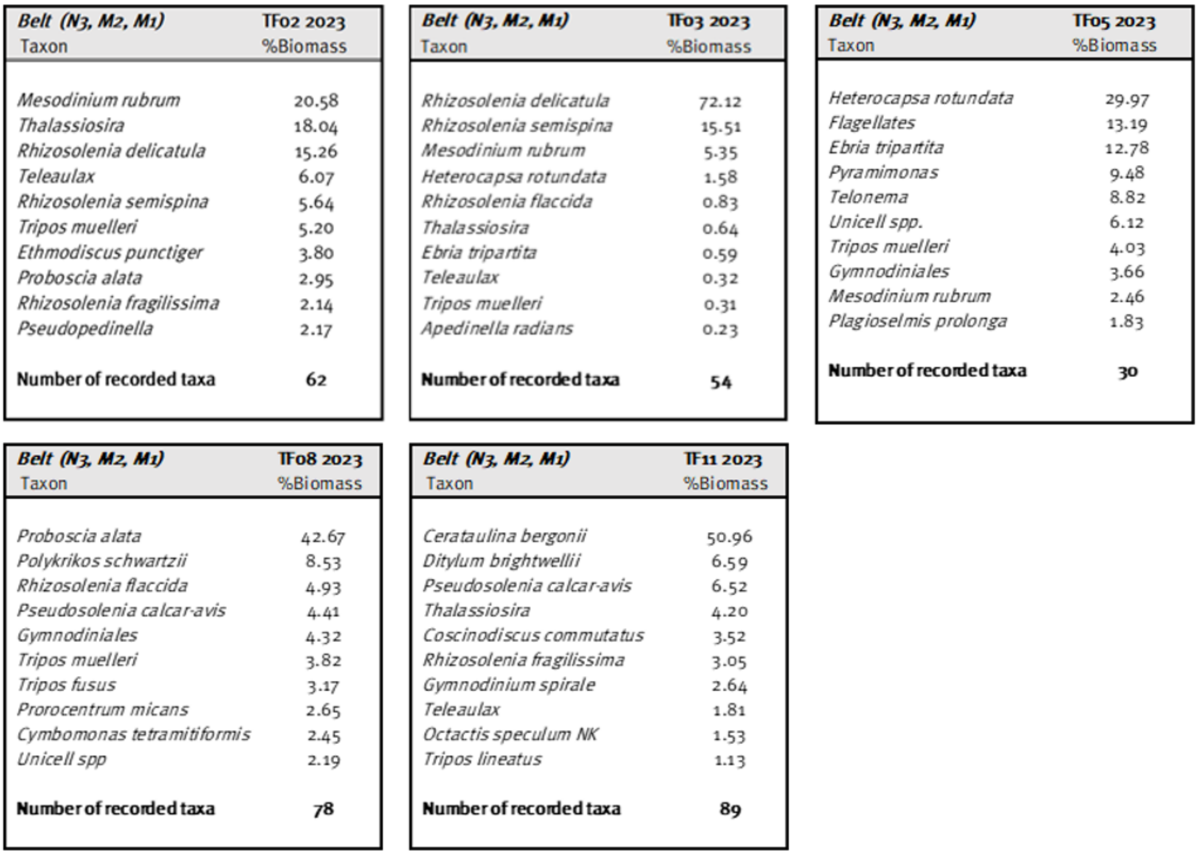
Fig. 3: Chl a *concentrations (left column) and biomass composition (right column) in 2023 at the sampling stations K8, K5 and K4 in the Arkona Basin. Chl* a *Samples were taken on northward (green) and southward return (grey) journey.*

4.1.2 Species diversity, non-indigenous species and harmful algal blooms

In 2023 alltogether 141 phytoplankton taxa were recorded in Belt Sea and Arkona Basin at the five monitoring cruises of 2023 (Table Appendix 1). This is five species less than recorded in 2022 when, however, a larger study area was considered.

In the Belt Sea, the highest number of taxa (89) was recorded in November. As in previous years, diatoms of *Rhizosolenia spp.*, *Proboscia alata* and *Cerataulina bergonii* were the most important biomass producers and particularly prominent in Belt Sea in March (~ 90 % of phytoplankton biomass), August and November (> 50 % at both cruises) (Table 5). *Tripos muelleri* and *Polykrikos schwartzii* (biomass ranks 7 and 9, Table Appendix 1) were the most important biomass producers among the dinoflagellates.

Table 5: The 10 most abundant species and number of recorded taxa in Belt Sea at the time of the 5 monitoring cruises in 2023. TF02 – TF11 refer to the months when the cruises took place (February to November).



Belt (N3, M2, M1) Taxon	**TF02 2023** %Biomass
Mesodinium rubrum	20.58
Thalassiosira	18.04
Rhizosolenia delicatula	15.26
Teleaulax	6.07
Rhizosolenia semispina	5.64
Tripos muelleri	5.20
Ethmodiscus punctiger	3.80
Proboscia alata	2.95
Rhizosolenia fragilissima	2.14
Pseudopedinella	2.17
Number of recorded taxa	62

Belt (N3, M2, M1) Taxon	**TF03 2023** %Biomass
Rhizosolenia delicatula	72.12
Rhizosolenia semispina	15.51
Mesodinium rubrum	5.35
Heterocapsa rotundata	1.58
Rhizosolenia flaccida	0.83
Thalassiosira	0.64
Ebria tripartita	0.59
Teleaulax	0.32
Tripos muelleri	0.31
Apedinella radians	0.23
Number of recorded taxa	54

Belt (N3, M2, M1) Taxon	**TF05 2023** %Biomass
Heterocapsa rotundata	29.97
Flagellates	13.19
Ebria tripartita	12.78
Pyramimonas	9.48
Telonema	8.82
Unicell spp.	6.12
Tripos muelleri	4.03
Gymnodiniales	3.66
Mesodinium rubrum	2.46
Plagioselmis prolonga	1.83
Number of recorded taxa	30

Belt (N3, M2, M1) Taxon	**TF08 2023** %Biomass
Proboscia alata	42.67
Polykrikos schwartzii	8.53
Rhizosolenia flaccida	4.93
Pseudosolenia calcar-avis	4.41
Gymnodiniales	4.32
Tripos muelleri	3.82
Tripos fusus	3.17
Prorocentrum micans	2.65
Cymbomonas tetramitiformis	2.45
Unicell spp	2.19
Number of recorded taxa	78

Belt (N3, M2, M1) Taxon	**TF11 2023** %Biomass
Cerataulina bergonii	50.96
Ditylum brightwellii	6.59
Pseudosolenia calcar-avis	6.52
Thalassiosira	4.20
Coscinodiscus commutatus	3.52
Rhizosolenia fragilissima	3.05
Gymnodinium spirale	2.64
Teleaulax	1.81
Octactis speculum NK	1.53
Tripos lineatus	1.13
Number of recorded taxa	89

In Arkona Basin (Table 6) the kleptoplastic ciliate *Mesodinium rubrum* ranked number 1 (3 for all samples, Table Appendix 1) at the three cruises in spring, contributing from 82 % in February to 58 and 23 % of biomass in March and May. In summer and autumn, diatoms were surprisingly prominent. While the spring community was thus a typical brackish Baltic Sea community, the summer and autumn aspects seemed to be strongly influenced by the more marine character of the Belt Sea. Such effect was less visible in the previuos years.

Table 6: The 10 most important species and number of recorded taxa in the Arkona Basin at 5 monitoring cruises in 2023. TF02 – TF11 refer to the months when the cruises took place (February to November).

Arkona (K8, K5, K4)	**TF02 2023**
Taxon	%Biomass
Mesodinium rubrum	81.78
Eutreptiella	4.06
Teleaulax	8.89
Heterocapsa rotundata	3.52
Gymnodinium	1.30
Plagioselmis prolonga	1.24
Unicell spp.	0.92
Aphanizomenon	0.89
Actinocyclus	0.88
Hemiselmis	0.68
Number of recorded taxa	**32**

Arkona (K8, K5, K4)	**TF03 2023**
Taxon	%Biomass
Mesodinium rubrum	58.62
Thalassiosira	17.69
Skeletonema marinoi	3.65
Eureptiella	2.80
Teleaulax	2.37
Gymnodiniales	2.08
Ebria tripartita	1.98
Chaetoceros castracanei	1.96
Gymnodinium corollarium	1.16
Aphanizomenon	1.08
Number of recorded taxa	**39**

Arkona (K8, K5, K4)	**TF05 2023**
Taxon	%Biomass
Mesodinium rubrum	23.36
Prymnesiales	22.87
Ebria tripartita	13.31
Heterocapsa rotundata	9.92
Pyramimonas	8.95
Unicell spp.	4.40
Plagioselmis prolonga	3.80
Telonema	2.30
Actinocyclus	2.10
Katodinium glaucum	1.27
Number of recorded taxa	**37**

Arkona (K8, K5, K4)	**TF07 2023**
Taxon	%Biomass
Rhizosolenia fragilissima	23.40
Tripos muelleri	14.65
Nodularia spumigena	8.12
Cymbomonas tetramitiformis	7.31
Polykrikos schwartzii	5.44
Ebria tripartita	5.38
Aphanizomenon	3.96
Gymnodiniales	2.93
Prorocentrum cordatum	2.49
Diplopsalis spp. CPX	2.54
Number of recorded taxa	**67**

Arkona (K8, K5, K4)	**TF11 2023**
Taxon	%Biomass
Cerataulina bergonii	48.71
Rhizosolenia fragilissima	36.91
Teleaulax	2.01
Mesodinium rubrum	1.81
Gymnodinium	1.29
Actinocyclus	1.16
Pyramimonas	1.14
Aphanizomenon	0.94
Eutreptiella	0.72
Prymnesiales	0.70
Number of recorded taxa	**51**

In 2023, 15 potentially toxic or harmful algal taxa were recorded in the study area (Table 7). While abundances were generally low and bloom concentrations were not encountered at the time of the monitoring cruises, the number of taxa had increased compared to 2022, when 8 taxa were recorded. The list now contained several known warm-water species such as *Karenia mikimotoi*, *Akashiwo sanguinea* and *Karlodinium veneficum*, which are potentially fish-killing, as well as *Azadinium* spp. (Fig. 4).

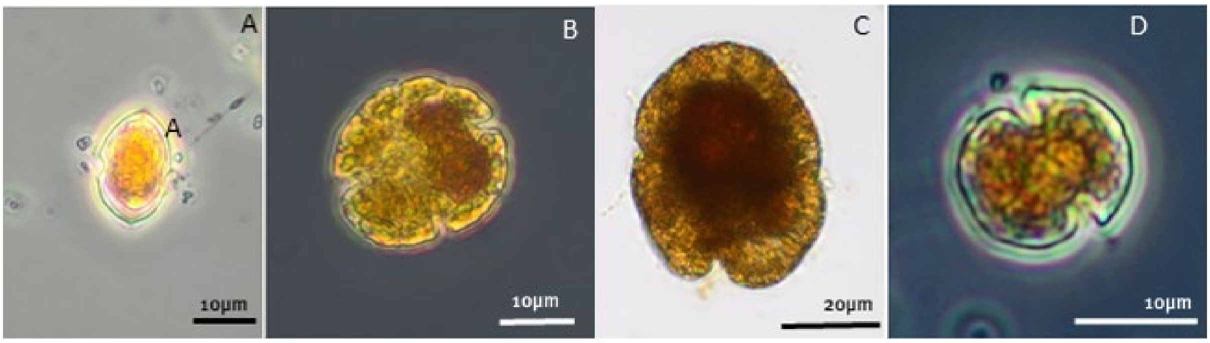


Fig. 4: Photographs of selected harmful algal bloom species present in the study area in 2023: A) Azadinium spinosum, B) Karenia mikimotoi , C) Akashiwo sanguinea, D) Karlodinium veneficum

Table 7: Harmful phytoplankton taxa in the study area in 2023. + = present, ++ = abundant (1-10 % biomass share), +++ = very abundant (> 10 % biomass share), ++++ = bloom (>50 % biomass share).

Station		TF0360	TF0012	TF0046	TF0030	TF0113	TF0109
		N3	M2	M1	K8	K5	K4
Species	Cruise	Belt	Belt	Belt	Arkona	Arkona	Arkona
Cyanophyceae							
Dolichospermum spp.	TF07 23	+	+	+	+	+	+
Nodularia spumigena	TF07 23	+	++	++	++	+++	++
Aphanizomenon sp.	TF02 23				+		+
	TF03 23			+	++	+	
	TF05 23				++	+	++
	TF07 23	+	+		++	++	++
	TF11 22			+		+	++
Dinophyceae							
Alexandrium pseudogonyaulax	TF07 23	+	+	+	+	+	+
Azadinium cf.	TF07 23	+		+			
Akashiwo sanguinea	TF07 23					+	
Prorocentrum cordatum	TF02 23		+				
	TF03 23		+	+			
	TF07 23		+	+	++		
	TF11 23	+	+	+		+	+
Dinophysis acuminata	TF02 23	++	+				+
	TF03 23						+
	TF05 23	+				++	
	TF07 23		+	+			+
	TF11 23			+		+	
Dinophysis norvegica	TF02 23	++					
	TF03 23	+			++		
	TF05 23	+					
	TF11 23	+					
Karenia mikimotoi	TF11 23	+					
Karlodinium veneficum	TF07 23	+	+	+	++	++	++
	TF11 23		+	+			
Bacillariophyceae							
Pseudo-nitzschia spp.	TF02 23		+				
	TF11 23		+				
Raphidophyceae							
Heterosigma akashiwo	TF02 23	++	+				
	TF11 23	+	+				
Dictyochophyceae							
Pseudochattonella farcimen	TF02 23	+					
Prymnesiales		+	+	+	+	+	+
	TF02 23	+	+	+	+	+	+
	TF03 23	+	+	+			++
	TF05 23		+	+	++	+++	+++
	TF07 23	++	++	++	++	++	++
	TF11 23	+	+	+		+	++

4.1.3 Cyanobacteria biomass 2023 in a long-term context

In 2023, the annual cyanobacteria biomass in the study area was assessed in a long term context at the six monitoring stations in Belt Sea and Arkona Basin. The index provides information on the general state of a sea area, assuming that high cyanobacteria biomass is a sign of environmental and ecological status deterioration in the Baltic Sea, where toxic or otherwise harmful cyanobacteria form blooms in summer. High cyanobacteria biomass may contribute to bottom water anoxia and oxygen deficiency in sediments with complex negative systemic implications. In 2023, cyanobacteria biomass was, at most stations, lower than during the previous year (Fig. 5). In the Belt Sea, cyanobacteria biomass was around (M2) or below (M1, N3) the 20 year mean, whereas in Arkona Basin cyanobacteria biomass was above the 20 year mean at the central and eastern sampling stations.

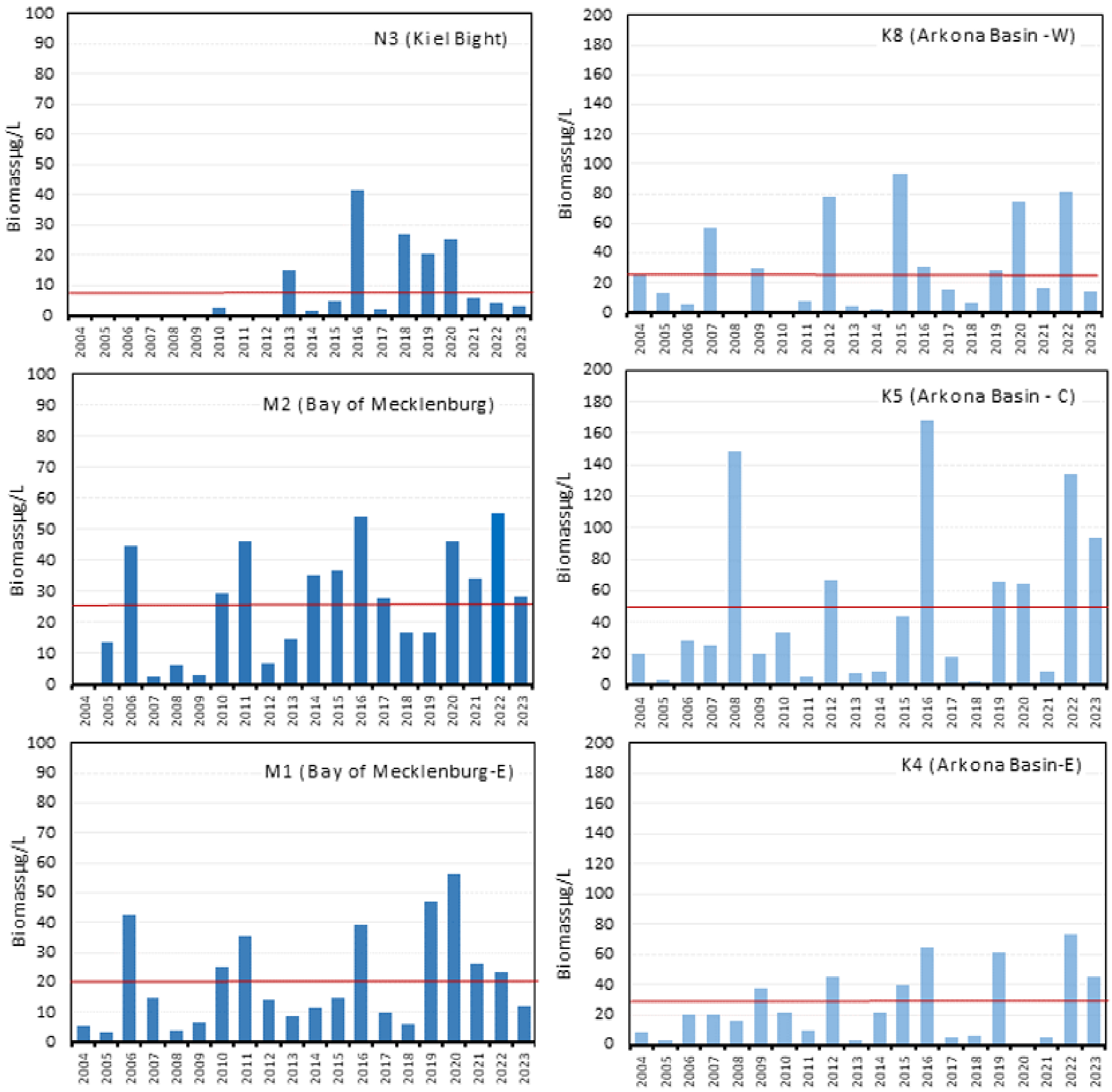


Fig. 5: Cyanobacteria biomass in a 20 year monitoring perspective at the six monitoring stations in Belt Sea and Arkona Basin. Bars display the summer biomass, whereas the red lines display the 20-years mean value. For location of stations see Fig. 1.

4.2 Mesozooplankton

4.2.1 Species composition and non-indigenous species

In 2023, a series of inflow events occurred that changed the usual environmental conditions in the different basins of the western Baltic Sea (for details see NAUMANN et al. 2024). Traces of a cold, saline inflow in December 2022 into the area were still visible in the bottom water of the Arkona Basin during February. In early summer, a baroclinic inflow build a thick bottom layer of saline water in the Belt Sea and replaced the cold bottom water in the Arkona Basin by very warm, but not exceptionally saline water (> 16 °C, ~18 PSU). At the end of the year, another inflow event occurred after the last monitoring cruise was completed.

In contrast to years with major Baltic inflows (MBI), the influence of the inflow events on the zooplankton species inventory was only minor in 2023. The record of 52 taxa was not different from the preceding years that lacked inflow events (44-50 taxa). The higher number of 32-34 taxa in the Belt Sea compared to 28-29 taxa in the Arkona Basin as well as the seasonal variation with a minimum in May in all areas also strongly resembled the preceding years (Fig. 6). During the last MBI in 2016, for instance, more than 70 taxa were recorded with a particularly high taxa number of 30-34 species during summer that was related to the occurrence of diverse meroplankton and also true marine copepod species such *Acartia clausi* or *Centropages typicus* (WASMUND et al. 2017, 2018b). In 2023, only few of these true marine species were observed and, thus, the usual euryhaline and brackish taxa dominated the taxa list (see Table Appendix 2). The low diversity is likely related to the low zooplankton stocks during winter when the first inflow occurred. This is reflected in single findings of the marine copepods *Microsetella* spp., *Calanus* spp. and *Oithona atlantica* or the cnidarians *Euphysa aurata* and *Rathkea octopunctata* mainly in the Arkona Basin where the residual of the December inflow was observed. During the warm inflows in summer 2023, further marine species such as the copepod *Euterpina* spp., the cladoceran *Penilia avirostris* and larvae of marine benthic genera (*Asterias*, *Carcinus*, *Phoronis*) occurred regularly in the plankton in the Belt Sea. The inflows, however, were apparently not sufficiently powerful to change the species spectrum further, particularly not in the Arkona Basin. In addition, several of the marine and brackish species – especially meroplankton and jellyfish – that were present in preceding, non-inflow years were lacking in 2023 and, thus, the taxa number remained on a lower level.

Apart from *Acartia tonsa*, no other species classified as non-indigenous (NIS) were found in 2023. This thermophilic copepod species is well-established in the Baltic Sea and was already introduced during the 1920s. It was recorded in German coastal waters for the first time in 1981 (GOLLASCH & NEHRING 2006)

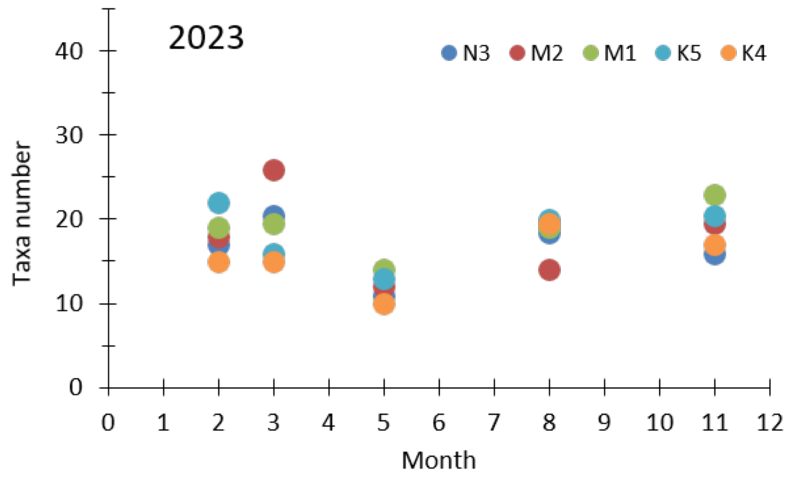


Fig. 6: Seasonal variation of the number of taxa occurring at the various monitoring stations in the south-western Baltic Sea in 2023 (OMBMP-N3: Kiel Bight, OMBMP-M2, -M1: Bay of Mecklenburg, OMBMP-K5, -K4: Arkona Basin)

The annual average composition was dominated by copepods in all areas in 2023 (Fig. 7). While this is commonly observed in the Belt Sea, it is rather unusual in the Arkona Basin and continues a series of similar observations in the area since 2019. This shift in dominance is mainly based on the decreasing abundance of other zooplankton than copepods, which remained rather constant. Thus, the contribution of copepods increased to 87 - 88 % (long-term: 60 - 64 %) at the cost of rotifers and particularly meroplankton in the Kiel Bight and the Bay of Mecklenburg. In the Arkona Basin, copepods usually contributed less to the community due to large concentrations of rotifers and cladocerans in spring and summer, respectively (e.g., WASMUND et al. 2019). In 2023, however, copepods had an unusual large contribution above the long-term average (69 %, long-term: 47 %) because cladocerans and rotifers displayed a low abundance. However, no major changes in the surface salinity of the Arkona Sea were observed in 2023 that could explain the decrease of cladocerans and rotifers (NAUMANN et al. 2024).

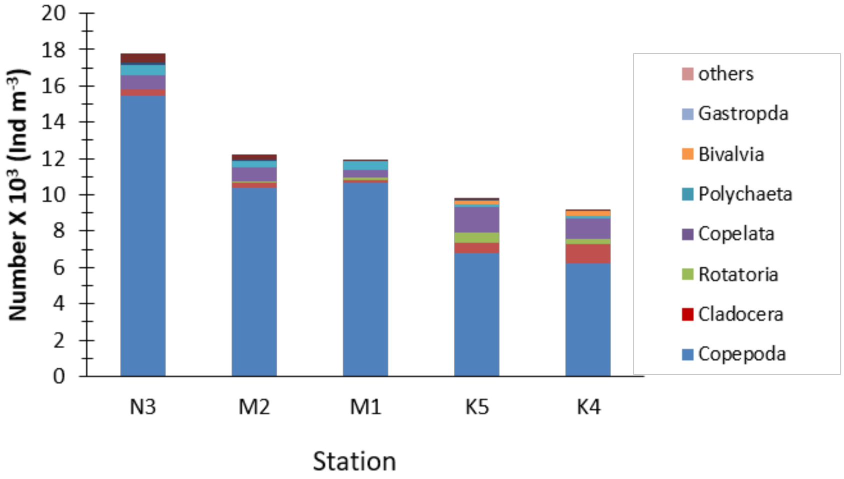


*Fig. 7: Annual mean abundance (Ind. * 10^3 m^{-3}) of the main groups of zooplankton in the south-western Baltic Sea. (OMBMP-N3: Kiel Bight, OMBMP-M2, -M1: Bay of Mecklenburg, OMBMP-K5, -K4: Arkona Basin*

4.2.2 Seasonal variation of zooplankton in the sub-areas

Kiel Bay (N3, Belt Sea)

The seasonal variation in the abundance of the zooplankton in the Kiel Bay was characterized by an unusual decline of the stocks during summer (Fig. 8). Winter stocks, in contrast, were comparable to earlier years (9,8 x 10^3 ind. m^{-3}) and were dominated by copepods and meroplankton, especially polychaete and bryozoan larvae. The appendicularian *Oikopleura dioica* was unusually abundant and contributed to 13 % to the stock. Before 2020, this species was rare during winter. In spring the zooplankton abundance doubled already in March (20,3 x 10^3 ind. m^{-3}) which indicates favourable conditions for an early zooplankton development. This is in agreement with winter-spring temperatures that were 2-3 °C above the long-term mean (NAUMANN et al. 2024). This early development with high spring stocks occurs regularly since 2014 when a series of continuously warm spring conditions began. In 2023, copepods were responsible for this increase, other groups remained low – especially meroplankton. This was also the case in May, when the zooplankton increased further to the annual maximum (Fig. 8, 38,8 x 10^3 ind. m^{-3}). Copepods alone accounted for more than 99 % of the stock. Rotifers and meroplankton commonly contribute to the zooplankton at this time, but were barely encountered in the samples in 2023.

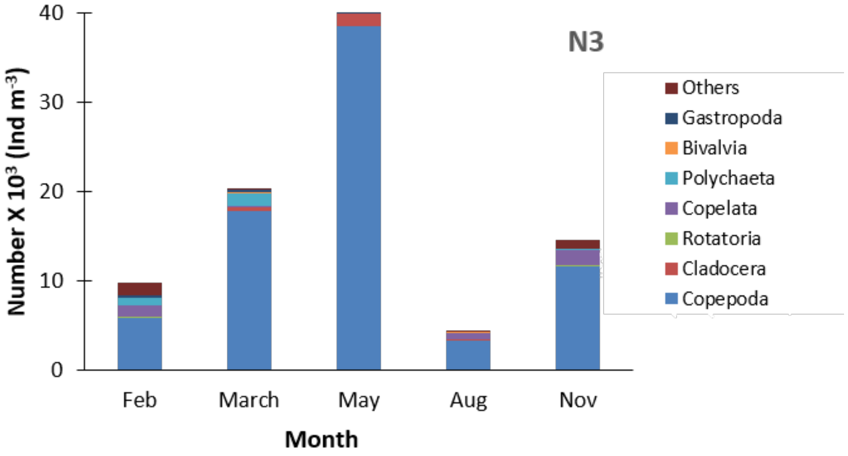


Fig. 8: Seasonal variation of the abundance of the major mesozooplankton groups in the Kiel Bight (OMBMP-N3) during 2023.

In summer, the large stocks observed during spring collapsed to less than 4,5 x 10^3 ind. m^{-3}, which is only ¼ of the usual stock size. The cause for this decline is difficult to evaluate and might be related to the baroclinic inflow of warm, salty water into to Belt Sea that apparently created unfavourable conditions throughout the water column, especially for a number of copepod species (see below). The temperature during August (> 18 °C) was, however, not exceptionally high. In addition, the salinity (17,2 PSU) was similar to spring conditions that normally favoured a diverse, abundant community. Thus, the decline in 2023 may be related to a combination of warm conditions with a high salinity in summer that might cause physiological stress to cold adapted species. Meroplankton, which can contribute up to 50 % of the zooplankton stock during summer, and the appendicularian *Oikopleura* also showed a considerably reduced abundance. Among the meroplankton, polychaete larvae replaced bivalve and gastropod larvae that usually dominate the community during summer. The zooplankton stock recovered in November with increasing stocks of copepods and *Oikopleura* when the salinity was still above average (19,4 PSU). Meroplankton, in contrast, remained lower than usual.

The composition of the copepod community reflected the general changes in 2023 during spring and summer (Fig. 9). The community was dominated by *Pseudocalanus* spp. (44 - 60 %) and *Oithona similis* (26 - 27 %) during February to May (Fig. 9). Particularly, *Pseudocalanus* spp. was found in close to maximum values observed in the time series during February and March. In the time series from 1998-2024 it reached a maximum abundance of 17 x 10^3 ind. m^{-3} in May. The dominance of this halophilic species is likely favoured by a higher salinity. However, it cannot be unequivocally related to the inflow of saline water during December 2022 because the revival of *Pseudocalanus* spp. was already observed in the previous year that lacked a similar inflow situation (ZETTLER et al. 2024). Thus, warmer winter temperatures and optimal food conditions might have favoured the species in recent years. Most of the other copepod species such as *Temora longicornis*, *Centropages hamatus* and *Acartia bifilosa* occurred in their usual abundance except *Acartia longiremis*, which was unusually rare.

With the arrival of the warm, saline water in summer 2023, the copepod community displayed a large shift in its composition from a cold to a warm water community (Fig. 9). Such a shift is not unusual for the Belt Sea during summer (DUTZ & WASMUND 2023). However, nearly all genera and species disappeared from the water column except the small cyclopoid copepod *Oithona*, which dominated the community by more than 90 %. Species like *T. longicornis, Pseudocalanus* spp., *A. bifilosa*, *A. longiremis* and *C. hamatus* that regularly occur in the area also during summer completely vanished. Together with *Oithona* the thermophilic species *Acartia tonsa* and *Paracalanus parvus* only occurred at low numbers. Despite the cooling and the recovery of the copepod stocks in November, no change in the composition of the community was observed (Fig. 9). *Oithona* still dominated with more than 97 %, while *A. tonsa* and *P. parvus* contributed to only less than 2 %.

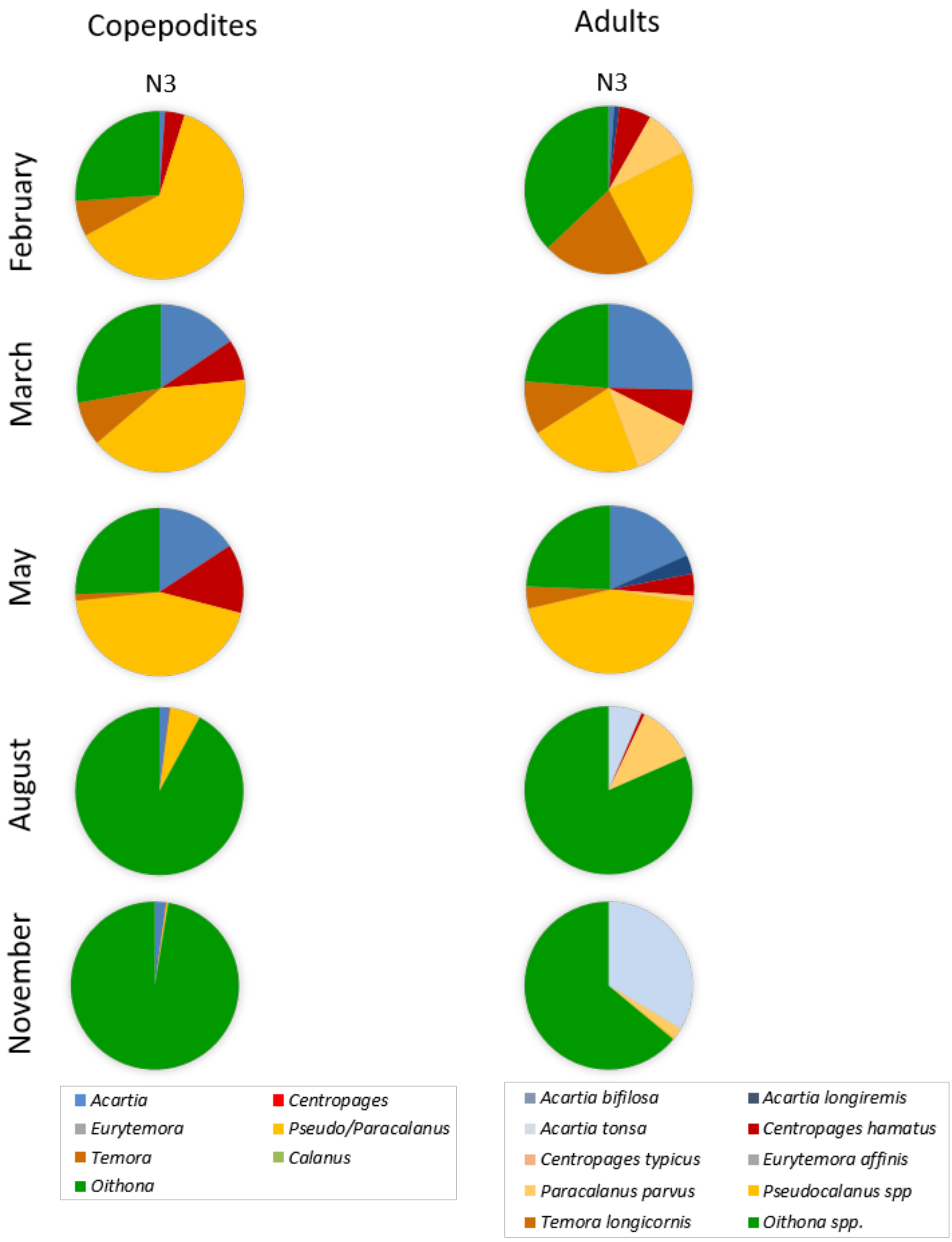


Fig. 9: Relative composition of the copepodites ($C_{I\text{-}V1}$, left panel) and adult copepods (C_{V1}, right panel) during the sampling months in the Kiel Bight (OMBMP-N3).

Bay of Mecklenburg (M2, M1, Belt Sea)

Due to the connection to the Kiel Bight via the Fehmarn Belt, the Bay of Mecklenburg often displays similar hydrographical conditions unless eastern winds transport central Baltic Sea water into the area. In 2023, the influence of the winter inflow of cold saline water and the subsequent warmer inflows in summer was clearly visible by a slightly higher salinity than usual in the surface water from winter to summer and by the unusually high salinity in the bottom during summer. As already stated (Chapter 4.2.1), the inflows had only a minor influence on the diversity of the zooplankton, and euryhaline and estuarine species dominated; only few true marine species were observed during spring and summer.

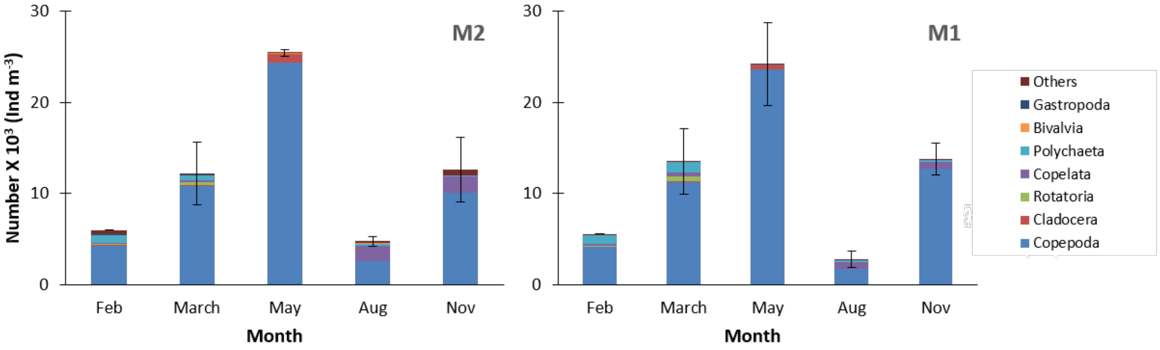


Fig. 10: Seasonal variation of the mean abundance of the major mesozooplankton groups in the Bay of Mecklenburg at station OMBMP-M2 and –M1 during 2023. Bars represent the mean (± standard deviation) of samples taken during out- and in-bound tracks (see Table 3).

Considering the similar hydrographical conditions throughout the Belt Sea, it is not surprising that the seasonal variation and community composition of the zooplankton at both stations in the Bay of Mecklenburg (M2, M1) strongly resembled the situation in the Kiel Bight. Thus, the development of the community started early in the year with a doubling of the stock size from February to March (Fig. 10). Copepods were even more dominant with a share of 70-72 % of the community and meroplankton – especially polychaetes - were abundant only in February. Depending on the hydrographical conditions, rotifers normally can contribute to the increase in the zooplankton in this area during May with up to 43 x 10^3 ind. m^{-3}. In 2023, however, very low numbers reflected the higher surface salinity during springtime. Similar to the Kiel Bight, the major increase in the zooplankton stock was, therefore, caused by the copepods which contributed 97 % to the maximum of 25 x 10^3 ind. m^{-3}.

In further analogy to the Kiel Bight, the zooplankton stock collapsed in August with only 3,7 x 10^3 ind. m^{-3} compared to the long-term mean of 23,7 x 10^3 ind. m^{-3}. This was again caused by a strong reduction in the copepods. In contrast to the Kiel Bight, appendicularians were abundant (*Oikopleura dioica*, up to 1,6 x 10^3 ind. m^{-3}) and contributed to 28-35 % to the zooplankton. The recovery of the stock was based on the increase of copepods that achieved the common abundance of 11,4 x 10^3 ind. m^{-3} in November. Appendicularians remained abundant though (1,6 x 10^3 ind. m^{-3}).

The seasonal variation in the composition of the copepods followed largely the variation in the Kiel Bight (Fig. 11). *Pseudocalanus* spp. dominated the community in winter and early spring (32-72 %), but the abundance of *Oithona* was generally lower (9-28 %). *Centropages* and *Temora* occurred at their usual density. In contrast, the stocks of *Acartia bifilosa* and *A. longiremis* were lower than usual. The increase to the seasonal maximum in May was caused by *Pseudocalanus* and *Acartia* and to a minor degree by *Temora longicornis* and *Centropages hamatus*. However, *A. longiremis* remained unusually low also in this area. With the collapse of the zooplankton stock in summer, the same shift to the unusual dominance of *Oithona* spp. occurred as in Kiel Bight (71-80 %). Again, *A. tonsa* and *Paracalanus parvus* were the only other species occurring with relevant density. With the recovery in November, the community changed only little.

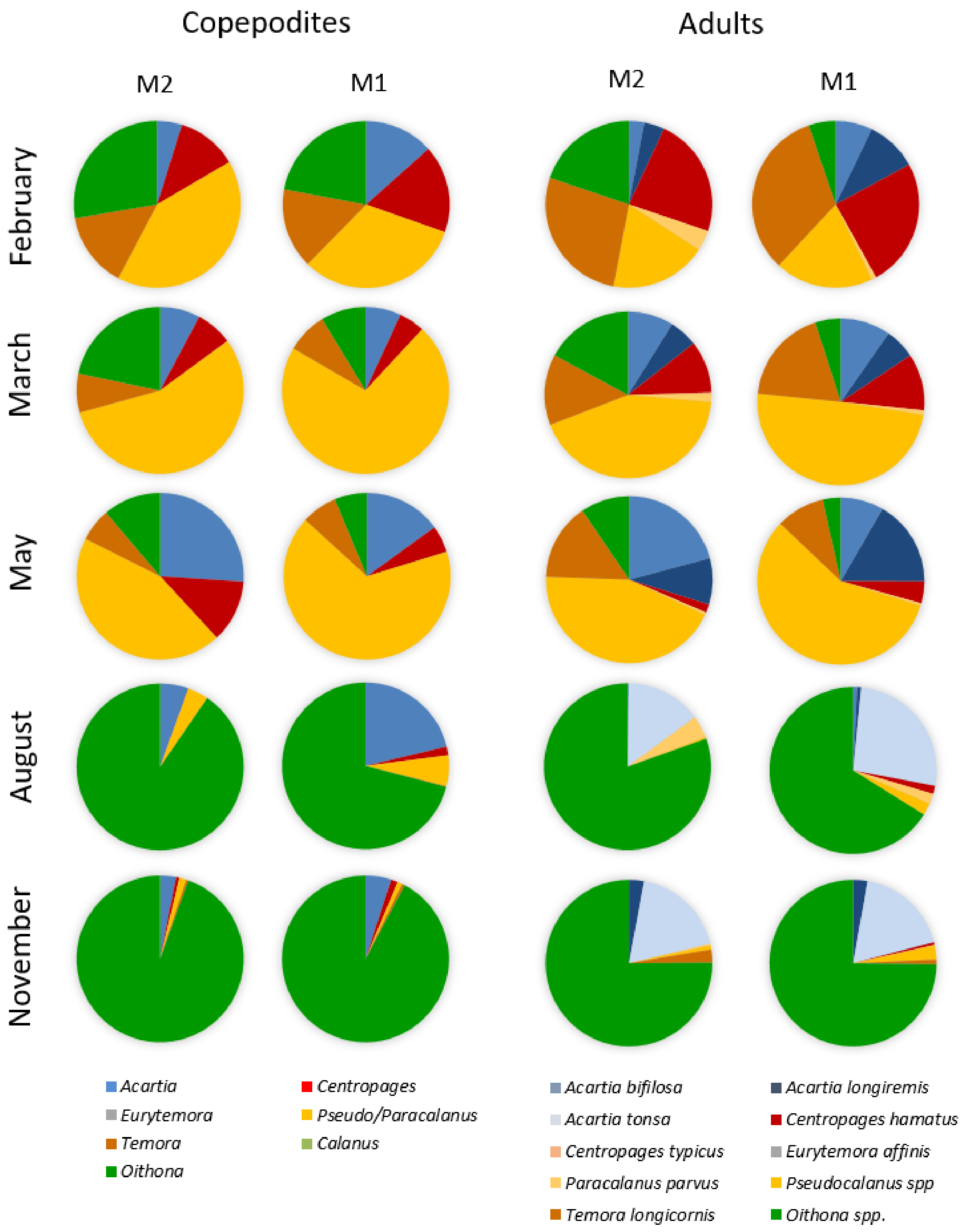


Fig. 11: Relative composition of the copepodites (C_{I-V1}, left panel) and adult copepods (C_{V1}, right panel) during the sampling months in the Bay of Mecklenburg (OMBMP-M2 and –M1).

Arkona Basin (K5, K4, Baltic Proper)

In contrast to the Belt Sea, the observed inflows had only a minor effect on the salinity conditions in the Arkona Basin. The surface salinity was only slightly (0,3-0,5 PSU) above the long-term values and in the range of the usual variability. The winter inflow during December 2022 left only traces of saline water of >20 PSU in the bottom water (lowest 3-4 m) of the basin. Sea water temperatures were, however, 0,6-0,8 °C higher in surface water during Feb-March and August. The most remarkable feature resulting from the warm summer inflows was the warm temperature in the deeper water in August that caused the entire water column to be warmer than 14,5°C. In November, temperatures in the bottom water were still warm (14,5°C) but the environmental conditions in the surface water were again as usual (10,4°C, 8,2 units). Only few true marine species were associated with the inflows and, thus, mainly euryhaline and estuarine species occurred - similar to the Belt sea.

The winter-spring transition showed the usual development of the community for the area, except that the abundance of meroplankton was lower than normal (Fig. 12). Copepods dominated the winter stocks (2,5-4,5 x 10^3 ind. m^{-3}) followed by low concentrations of appendicularians and polychaete larvae. In comparison to the Belt Sea, a delay in the increase in copepod abundance from March to May is common in the Arkona Basin and is caused by the delay of the warming of the water column (DUTZ & WASMUND 2023). Thus, the increase in the zooplankton in March is usually related to other groups. In 2023, a high abundance of the appendicularian *Fritillaria borealis* was observed with the largest concentration for this season in the entire time series since 1998 (5,2 x 10^3 ind. m^{-3}). With the response of the copepods to the warming of the water column in spring, the abundance of zooplankton rose to the annual maximum of 19,9 x 10^3 ind. m^{-3} in May. Uncommon for this time of the year, copepods dominated the community (> 80 %) but the total abundance was rather low. This is related to a lack of the abundant rotifer *Synchaeta* spp. that usually occur at higher numbers in May (up to 77,6 x 10^3 ind. m^{-3}).

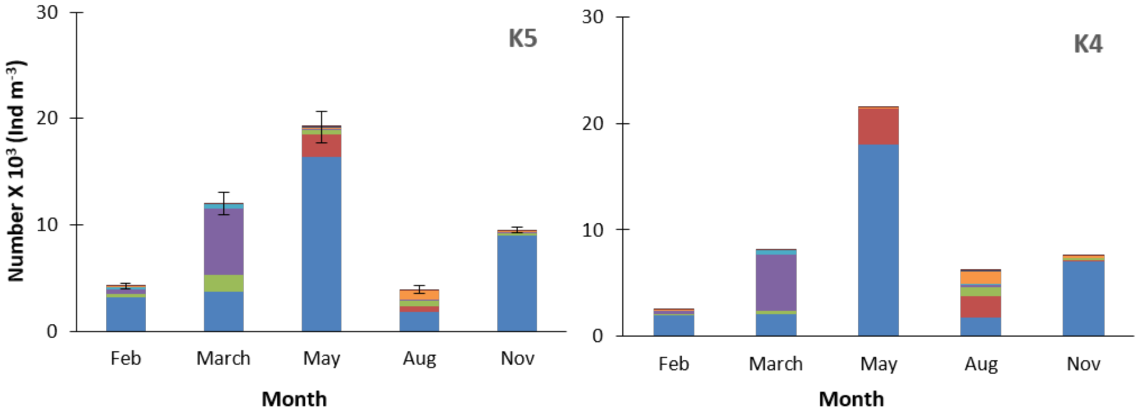


Fig. 12: Seasonal variation of the mean abundance of the major mesozooplankton groups in Arkona Basin at station OMBMP-K5 and – K4 during 2023. Bars represent the mean (± standard deviation) of samples taken during out- and in-bound tracks (see Table 3).

Despite the different hydrographical conditions, the unusual minimum of the zooplankton stocks in August occurred also in the Arkona Basin (3,8-6,2 x 10^3 ind. m^{-3}) and exceptionally low numbers of the cladoceran *Bosmina* spp. (1,0 x 10^3 ind. m^{-3}) were observed. The species occurs regularly in one order of magnitude higher density in the area. Nevertheless, also copepods were found at their lowest density observed during this season in the entire time series since 1998 and meroplankton was unusually rare, as well. This might reflect the unusually warm conditions during summer in the whole water column with temperatures higher than 19°C at the surface and up to 5°C warmer below the thermocline. Compared to the Belt Sea, the recovery of the zooplankton stocks was only moderate. An average of 8,8 x 10^3 ind. m^{-3} is below the long-term mean of 11,9 x 10^3 ind. m^{-3}. Copepods were the dominating the community with their usual abundance (7,1-9,2 x 10^3 ind. m^{-3}), while cladocerans, rotifers, appendicularians and meroplankton occurred at low concentrations.

While *Pseudocalanus* spp. occurred during winter and spring at a higher than the usual density, the species' dominance was not as pronounced as observed in the Belt Sea and other genera/species were equally important (Fig. 13). Due to its cold water affinity, the stocks of *Pseudocalanus* rose already in March when it contributed to 29-60 % to the copepods, followed by *Acartia* (23 %). With the warming of the water column, *Temora*, *Centropages* and *Acartia* were equally abundant. Among the latter, *A. longiremis* dominated (38 %) as usual. With the collapse of the zooplankton community, the cyclopoid *Oithona* became the dominant genus. However, a complete replacement of the spring community by thermophilic copepods similar to the Belt sea was not observed. Thus, *T. longicornis*, *C. hamatus* and *A. longiremis* were common together with *A. tonsa* and increased their contribution on the cost of *Oithona* after the recovery of the stock in November (Fig. 13).

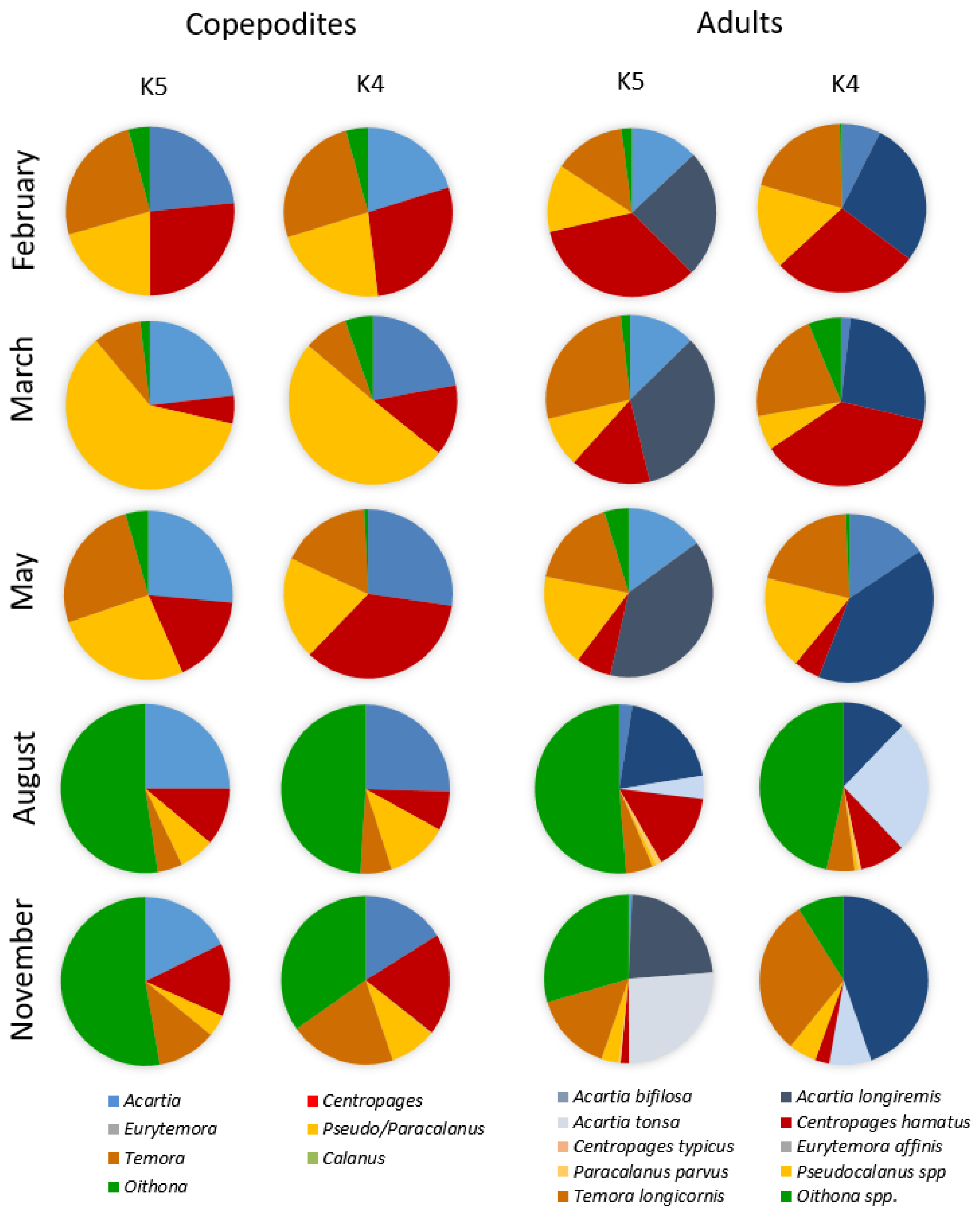


Fig. 13: Relative composition of the copepodites (C_{I-V1}, left panel) and adult copepods (C_{V1}, right panel) during the sampling months in the Bay of Mecklenburg (OMBMP-M2 and –M1).

4.2.3 Long-term trends

Annual mean abundance

The long-term change in the annual mean abundance of the major groups of the zooplankton – copepods, cladocerans and rotifers –displayed a rather similar pattern of variation with time in the three basins between 1998 and 2023 (Fig. 14), but with relevant differences among the groups. Copepods usually dominate the zooplankton in the Kiel Bight, the Bay of Mecklenburg and the Arkona Basin with a mean of 66, 60 and 47 %, respectively. The gradual decrease is owed to the raising influence of the Baltic Proper as can be seen from the reduction of the surface salinity and the associated increase in the abundance of cladocerans and rotifers. Nevertheless, their long-term patterns were rather similar in the three basins and did not show any clear trends. They displayed irregular variations with some more or less pronounced minima in the periods 2005-2007, 2014-2015 and 2019-2020. In 2023, the annual mean of copepods was higher or close to the long-term mean of 12,4 and 10,5 x 10^3 ind. m^{-3} in the Kiel Bight and the Bay of Mecklenburg, respectively, and slightly below the long-term mean of 7,8 x 10^3 ind. m^{-3} in the Arkona basin. The difference likely originates from the early development and associated high concentrations in March and May 2023 in the Belt Sea that compensated for the low summer abundance. In the Arkona Sea, this compensating effect is smaller due to the delayed increase in copepod stocks in spring.

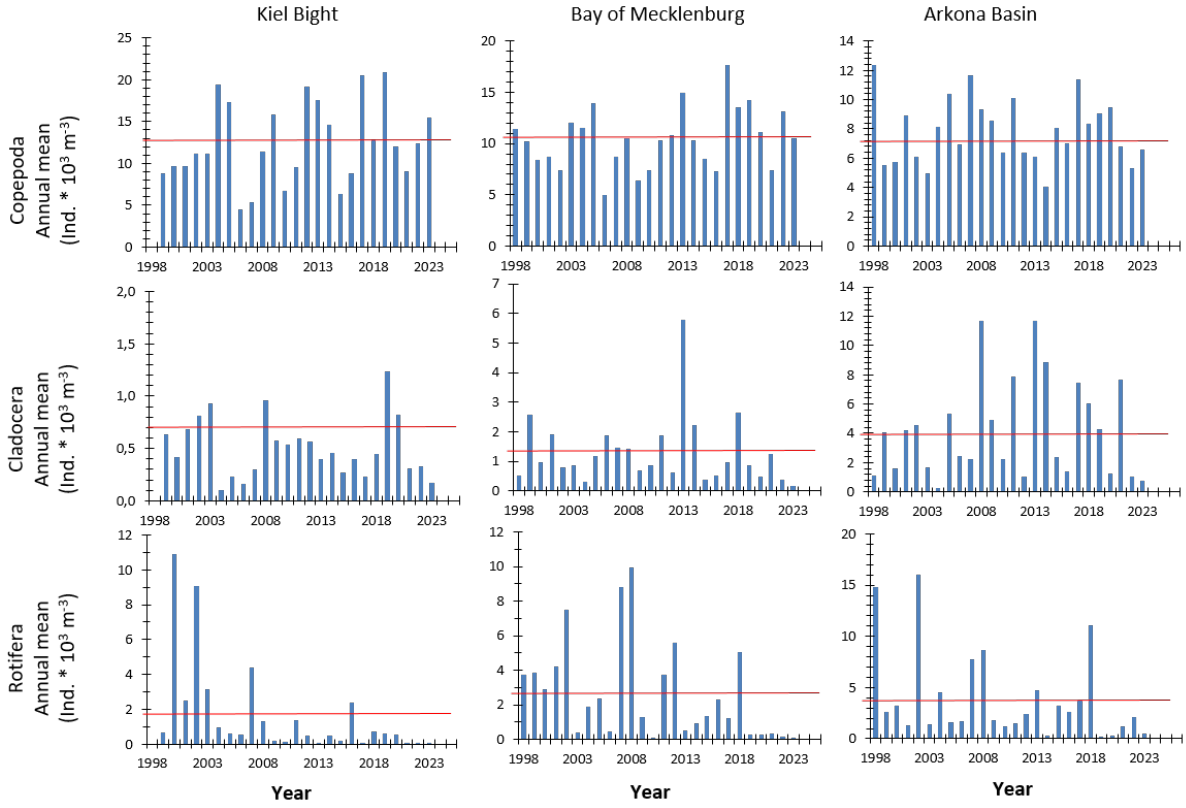


Fig. 14: Long-term variation 1998 – 2023 of the annual mean abundance of the three dominant zooplankton groups in the Kiel Bight (OMBMP-N3), the Bay of Mecklenburg (OMBMP-M2, -M1) and the Arkona Basin (OMBMP.K5, -K4). Bars display the mean of the mean seasonal abundance of stations in each Basin. Note the different scales in the annual means.

In contrast to the copepods, the cladocerans and, in particular, the rotifers displayed a rather low mean abundance in the last 3-5 years and independent of their relative contribution to the zooplankton in the area (Fig. 14). In the Belt Sea their abundance decreased to less than 100 ind. m^{-3} in 2023, which is rather low compared to the long-term mean of 1.660 - 2.650 ind. m^{-3} in the Kiel Bight and the Bay of Mecklenburg, respectively. In the Arkona Basin rotifers are more common, especially in spring. Here, their mean abundance in 2023 decreased to less than 500 ind. m^{-3} compared to the long-term mean of 3.800 ind. m^{-3}. This is equivalent to a reduction in the contribution over the years from 22 % to 5 % of the zooplankton stock.

The causes for the decline of rotifers and cladocerans and, thus, the zooplankton stock can be manifold and may originate from changes in primary production, predation or warming of the water column during the recent years as can be inferred from decreasing trends of zooplankton abundance in the north Sea (e.g., GREVE et al. 2004). In the Baltic Sea, the potential causes cannot unequivocally be evaluated due to a lack of data from comparable time series of primary production or potential predators such as gelatinous zooplankton.

Zooplankton biomass and mean size

The zooplankton stock and mean size of relevant taxa are part of the core indicator of the same name (in short MSTS) for the state of the pelagic ecosystem of the Baltic Sea in the framework of HELCOM (HELCOM 2023c). In the western Baltic Sea, the indicator is not fully implemented and threshold values for the evaluation of zooplankton status in summer are not established, yet.

In 2023, the biomass of the zooplankton during summer displayed the lowest values recorded in the long-term time series from 1998 - 2023 in the Kiel Bight, the Bay of Mecklenburg and the Arkona Basin (Fig. 15).

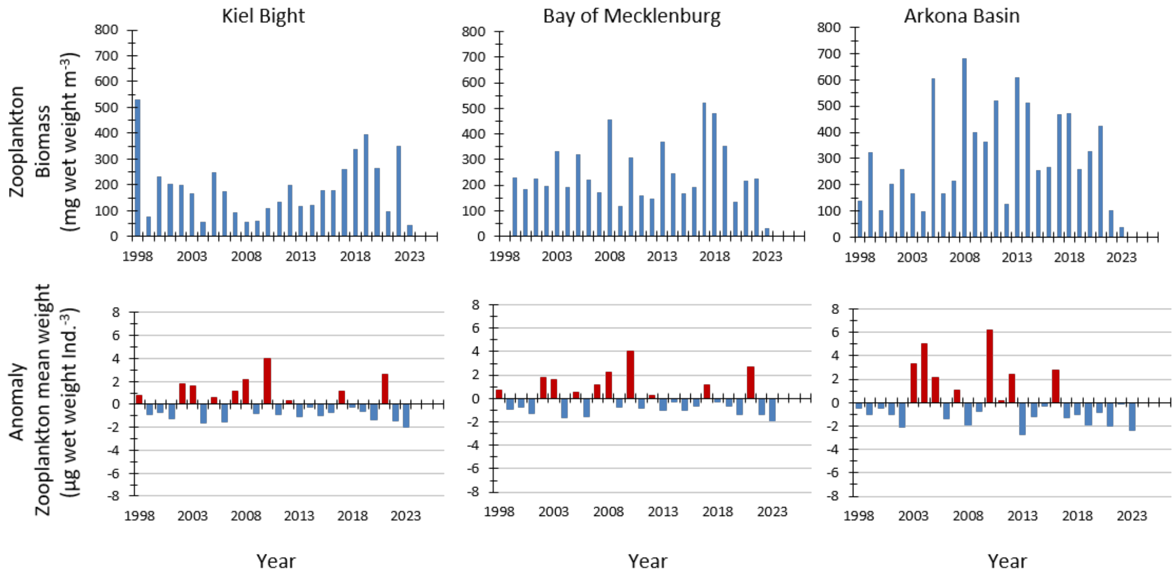


Fig. 15: Long-term variation (1998 – 2023) of the mean biomass and the anomalies of mean size of selected zooplankton groups relevant for the HELCOM zooplankton indicator "Mean size and total stock" (MSTS) in August 2023 in the Kiel Bight (OMBMP-N3), the Bay of Mecklenburg (OMBMP-M2, -M1) and the Arkona Basin (OMBMP.K5, -K4). Bars display the mean of stations in each Basin.

The zooplankton mean size is calculated as quotient of the mean biomass and the mean abundance in summer (Fig. 15). There is a predominance of negative deviations from the average mean weight of 10,4-11,5 µg wet weight ind.$^{-1}$ during summer in all areas since 2010. Usually rotifers and cladoceran such as *Synchaeta* or *Bosmina,* among others, are responsible for negative deviations in the mean size of the zooplankton in the Baltic Sea. In the western Baltic Sea, the negative deviations occur during a time with decreasing contributions of this groups and are, therefore, also associated with the increasing dominance of the small cyclopoid copepod *Oithona* in the area (compare chapter 4.2.2, DUTZ 2018, DUTZ et al. 2022, ZETTLER et al. 2024).

4.3 Macrozoobenthos

4.3.1 Sediments and oxygen

At all monitoring stations, samples were taken with additional Van Veen grabs for the analysis of the particle size and organic content of sediment. CTD dips were done to determine associated parameters such as oxygen concentrations and near-bottom salinity (Table 8). Chemical parameters were measured in all samples taken during the five cruises per year (not content of this report, see NAUMANN et al. 2024). A good oxygen supply was observed at all stations during the samplings almost all year round. No values lower than 2 ml l^{-1} were measured at any station during the five cruises. Fig. 16 shows an example for Arkona Basin (K4), where oxygen demands have been frequently observed in the past.

For almost all stations, the salinity was at a long-term average value for the respective area. The autumn bottom water salinity ranged from west to east between 20,7 and 8,3 PSU (Table 8).

Table 8: Abiotic parameters at 8 monitoring stations in autumn 2023 (Org = organic content of sediment in %, GS = median grain size in µm, O_2 = oxygen content of near bottom water in ml l^{-1}, S = salinity at near bottom water in PSU). HUB based on Marx et al. (2024)

Station	Org	GS	O_2	S	MSRL (BHT)	
	%	(µm)	(ml l^{-1})	(PSU)	Broad habitat types	HUB
N3	1,04	240	4,61	20,7	infralittoral sand	AA.J3L3
N1	2,63	374	5,8	19	circalittoral mud	AB.H3L3
M2	9,36	15	3,81	19,2	circalittoral mud	AB.H3L3
OM18	1,91	144	4,75	18,8	infralittoral sand	AA.J3L3
K8	0,25	220	6,48	9,4	circalittoral sand	AB.J3L9
K4	10,84	11	2,89	16,4	circalittoral mud	AB.H3L9
K3	0,53	221	5,1	10	circalittoral sand	AB.J3L1
OM160	0,26	197	6,5	8,3	circalittoral sand	AB.J3L9

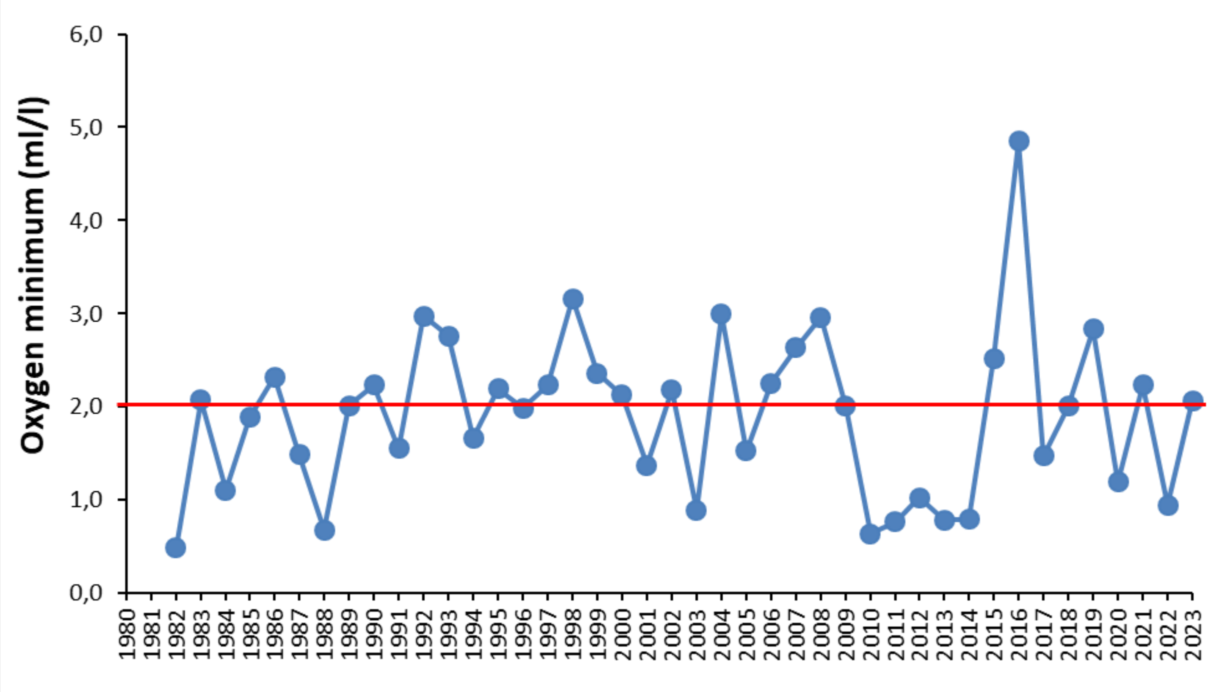


Fig. 16: The lowest annual oxygen levels in the near-bottom water of the Arkona Basin (K4) from 1980 to 2023. The red line shows the threshold value of 2 ml l^{-1}.

4.3.2 Macrozoobenthos at the stations

Our monitoring stations belong to five different macrozoobenthic communities along the salinity and depth gradient (see Gogina et al. 2016). Regarding the MFSD broad habitat types (EU-Kommissionsbeschluss 2017/848/EU 2017) they belong to three categories (Table 8). Using the HELCOM Underwater biotope and habitat classification system (Table 8), the stations could be assigned to five categories (Zettler & Darr 2023, Marx et al. 2024).

Compared with the period 1991 to 2023, the number of species was relatively high at 138 (Table Appendix 3, Fig. 17 and Fig. 20). At three stations (K8, K3, K4) we observed slightly higher diversity as the median. At almost all stations, the yearly values were similar to the long-term mean. Only in the Kiel Bay (N3) we observed higher diversity and at station OM18 slightly lower values (Fig. 17). The often high density of bivalves, such as at stations N3 (*Astarte borealis*) and OM160 (*Mya arenaria*), should be emphasised (Fig. 18).

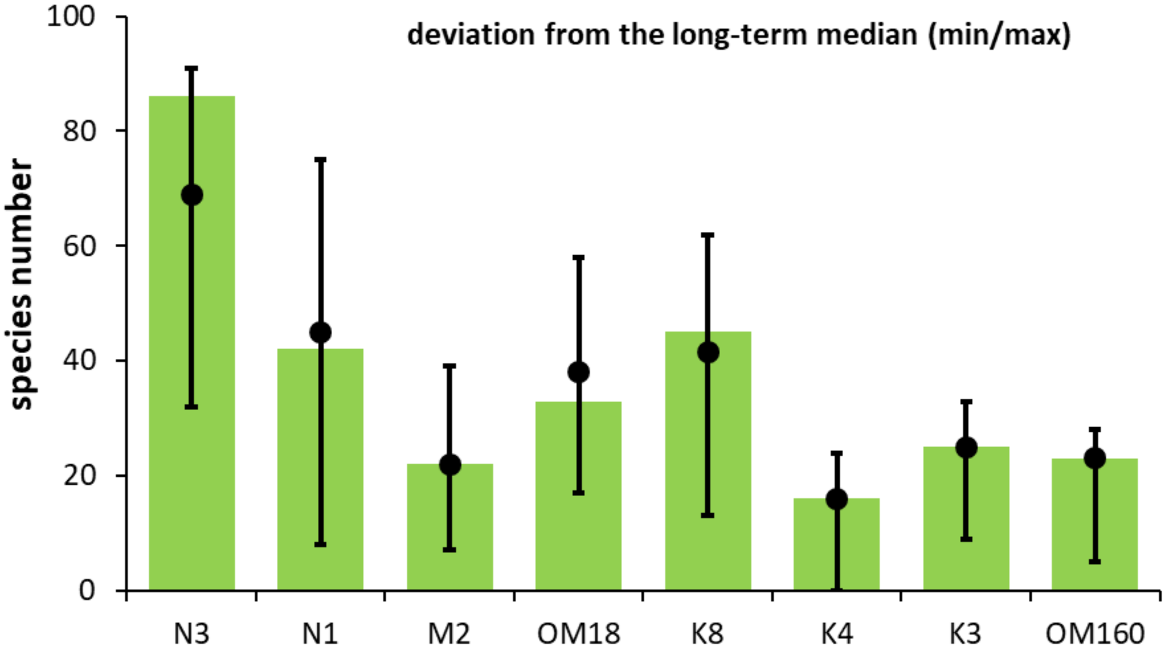


Fig. 17: Number of species (columns) of macrozoobenthos at eight monitoring stations in November 2023. The median values of the years 1991 to 2023 are shown as dots; the minimum and maximum values are indicated as interval. The stations are plotted from west to east (Kiel Bight = N3 to Pomeranian Bay = OM160).

Fig. 18: Samples of Kiel Bay (N3) with a dense population of Astarte borealis *(top) and* Mya arenaria *in the Pomeranian Bay (OM160) (bottom).*

In general, neither a significant increase nor decrease in macrozoobenthos species number was observed in 2023. However, at some stations new observed species (never observed during the last 20 years at these stations) were found. These species are listed below:

=›N3: *Filellum serpens*, *Barentsia sp., Onchidoris muricata, Parthenina interstincta, Erinaceusyllis erinaceus, Parexogone hebes, Platynereis dumerilii, Dexamine spinosa, Megamphopus cornutus, Metopa pusilla, Nippoleucon hinumensis*

=›N1: *Philine punctata*, *Aricidea minuta*, *Pycnogonum litorale*

=›M2: none

=›OM18: *Philine punctata, Spisula subtruncata, Mediomastus fragilis*

=›K8: *Ensis leei*

=›K4: none

=›K3: *Eucratea loricata*

=›OM160: *Asterias rubens*

To our knowledge, *Philine punctata* has not yet been recorded in the Baltic Sea (except the Kattegat). In addition to the detection at station N1 and OM18 this year, we were able to observe it at several locations in Kiel and Mecklenburg Bight outside the current monitoring programme.

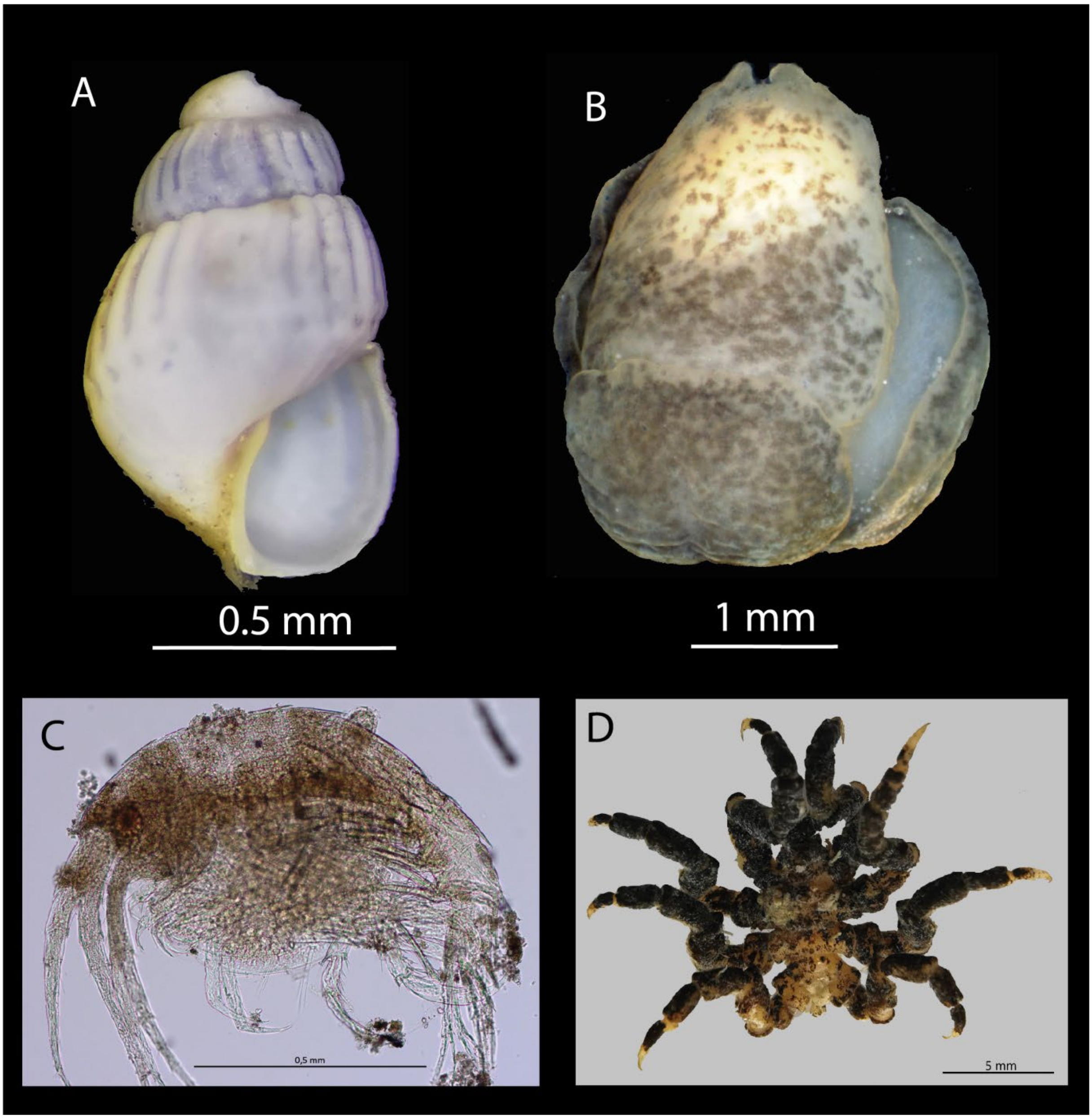


Fig. 19: Some of the new species found during the monitoring activities in November 2023: A) Parthenina interstincta *(Stn. N3), B)* Philine punctata (Stn. N1)*, C)* Metopa pusilla *(Stn. N3) and D)* Pycnogonum litorale *(Stn. N1)*

Fig. 20 shows the taxa found at our eight monitoring stations in 2023 and the total number of species found in measurements since 1991 (for all 8 stations we usually sample). As in the years before the Annelida (here mainly Polychaeta) emerged as the group that is richest in species number, numbering 109 in total; in 2023, 48 species were identified. Other species-rich groups in 2023 were Mollusca (30), Crustacea (22), Bryozoa (11) and Cnidaria (7).

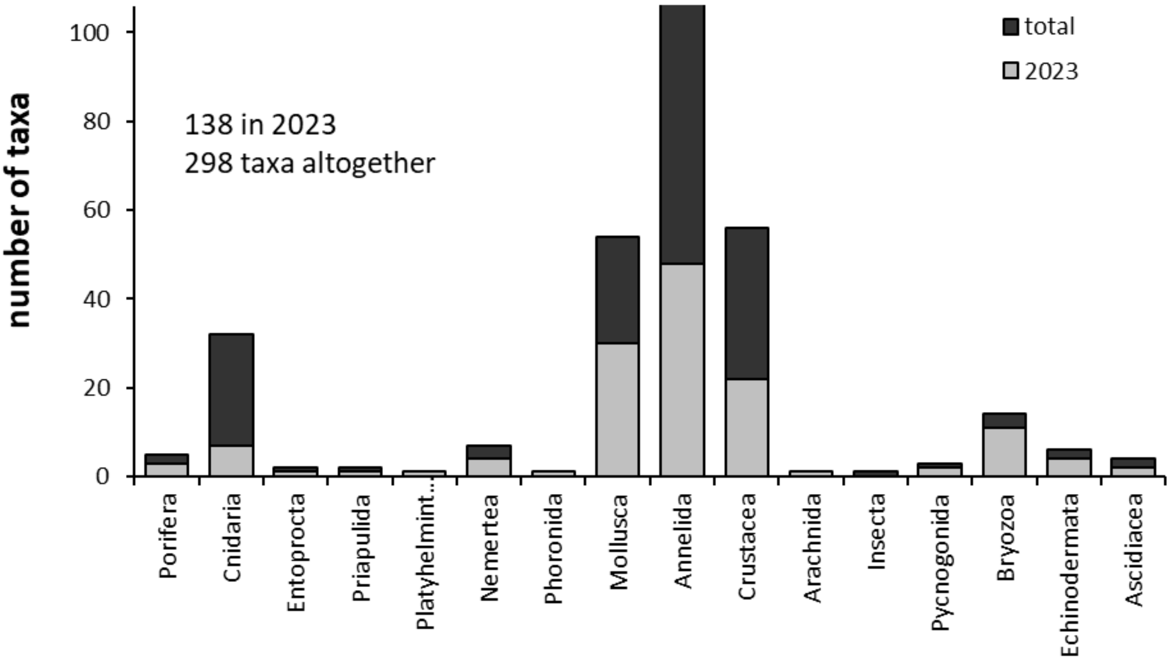


Fig. 20: Taxonomical classification of macrozoobenthos at the eight monitoring stations in November 2023 (grey). The species number of the entire monitoring period from 1991 to 2023 at 8 stations is also indicated (black columns).

Depending on the sea area, abundances varied between 331 (Arkona Basin) and 6775 ind. m^{-2} (Pomeranian Bay) (Fig. 21, Table Appendix 3). At most stations, the abundance is slightly (M2, OM18) or even significantly (N3, N1, K8, OM160) below the long-term average (Fig. 21) or within the long term mean (K4). The only exception is station K3 in the northern Pomeranian Bay, where a slightly higher abundance was observed.

Which species was dominant in a given sea area varied greatly; it depended essentially on salinity and substrate (Table 8). While the abundances were mainly dominated by polychaetes, bivalves determined the biomass. In the western part (N3 to OM18), the polychaetes *Ampharete baltica*, *Scoloplos armiger* and the phoronid *Phoronis* sp. dominated the density. *Scoloplos armiger* played a dominant role at several stations. Other dominant species at different stations were the polychaetes *Ampharete cirrata*, *Pygospio elegans* and *Terebellides stroemii*, the bivalves *Kurtiella bidentata* and *Mytilus edulis* (see Table 9 for detailed information). At the western stations (N3 to OM18) *Arctica islandica* was the dominant biomass species, while at the eastern stations (K8, K4, K3, OM160) *Macoma balthica*, *Mytilus edulis* or *Mya arenaria* were more important.

Table 9: Dominance (%) in abundance and biomass at the eight monitoring stations during November 2023. The stations are plotted from west to east (Kiel Bight = N3 to Pomeranian Bay = OM160).

Abundance in %	**N3**	**N1**	**M2**	**OM18**	**K8**	**K4**	**K3**	**OM160**
Ampharete baltica		16						
Ampharete cirrata						28		
Arctica islandica			16					
Kurtiella bidentata	22			13				
Mytilus edulis					13		58	
Peringia ulvae			30					69
Phoronis sp.	21	46	13	18				
Pygospio elegans					24			20
Scalibregma inflatum	18							
Scoloplos armiger				29		21	11	
Terebellides stroemii						14		
Biomass in %								
Arctica islandica	39	99	99	63		49		
Astarte borealis	39				37			
Astarte elliptica						15		
Crangon crangon							37	
Macoma balthica						14	22	36
Mya arenaria								46
Mytilus edulis					54		20	
Peringia ulvae								12
Scoloplos armiger				12				

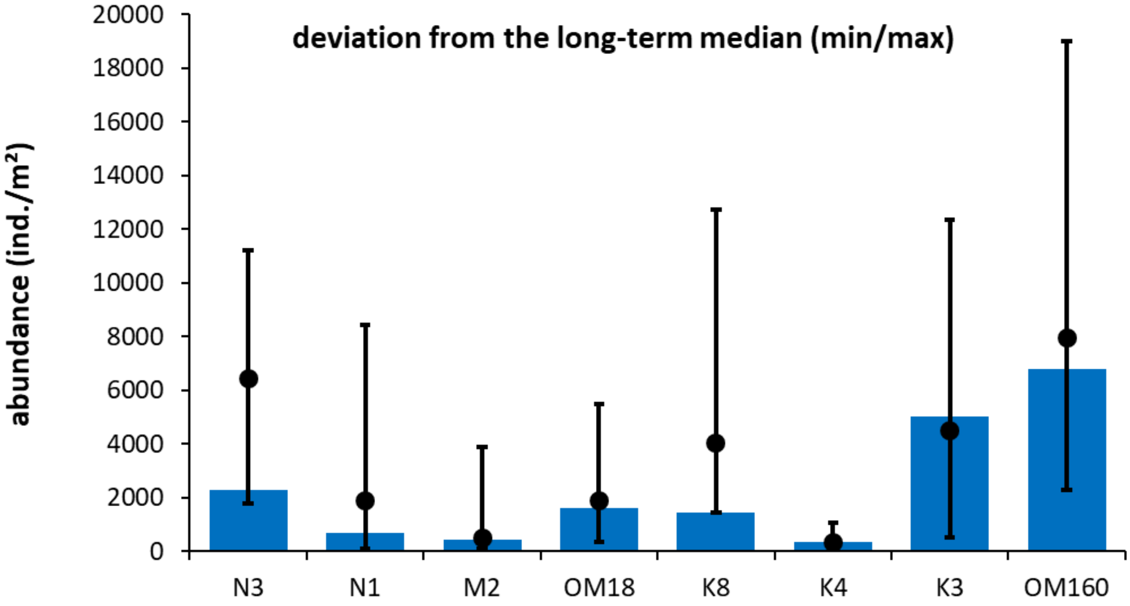


Fig. 21: Total abundances (columns) of macrozoobenthos at eight monitoring stations in November 2023. The median values for the years 1991 to 2023 are shown as dots; the minimum and maximum values are indicated as intervals. The stations are plotted from west to east (Kiel Bay = N3 to Pomeranian Bay = OM160).

Compared with their long-term averages, almost all stations showed a lower total biomass in 2023 (Fig. 22). Significantly higher than the long-term median were the values in the Mecklenburg Bay (M2), caused by the high dominance of *Arctica islandica* (Fig. 23). At the Arkona Basin (K4), the biomass was within the long-term average (Fig. 22).

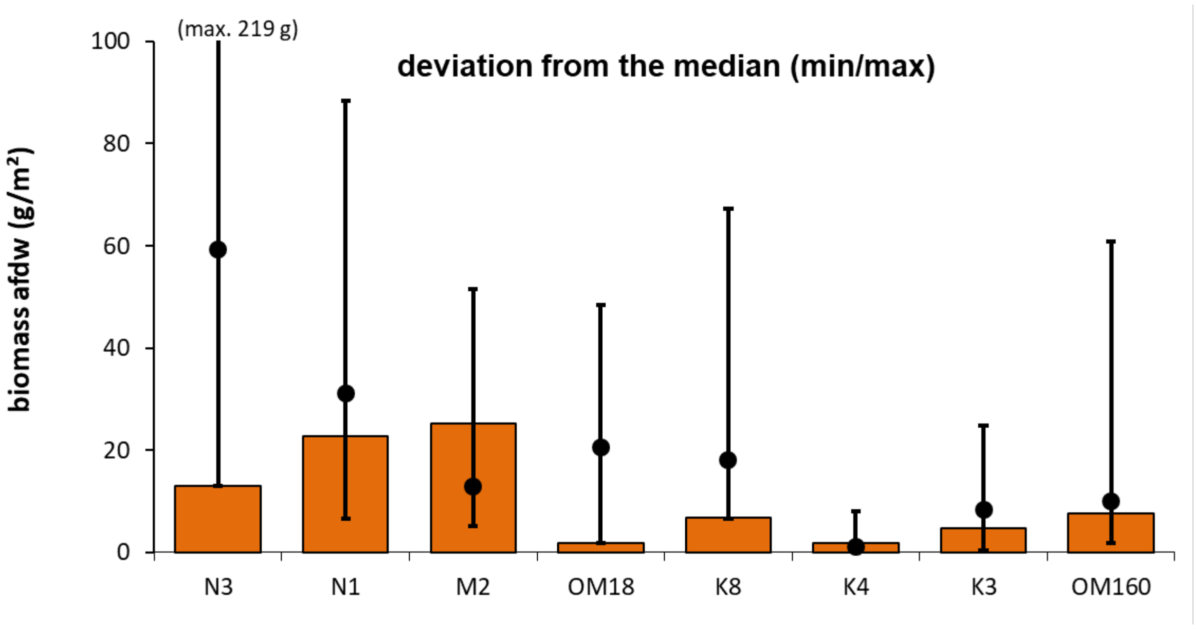


Fig. 22: Total biomass (columns, as ash free dry weights, afdw) of macrozoobenthos at eight monitoring stations in November 2023. The median values for the years 1991 to 2023 are shown as dots and the minimum and maximum values are indicated as intervals. The stations are plotted from west to east (Kiel Bight = N3 to Pomeranian Bay = OM160).

Fig. 23: In 2023 the dominant species of the grab samples in the Mecklenburg Bay (M2) was Arctica islandica*.*

Both for abundance and biomass, analysis of our long-term data in part revealed considerable fluctuations that are illustrated as error bars (min/max) in the Fig. 21 and Fig. 22. The fluctuations essentially relate to the population dynamics of long-lived species (especially molluscs) in terms of biomass or the mass development of opportunistic species (e.g. polychaetes). Another general influence can be a population collapse following a phase of oxygen deficiency (although no lack of oxygen was observed in our 2023 data). Not least, however, the randomness of sampling and the clustered distribution of organisms are responsible for these fluctuations in the data. Human induced direct effects are not evidently visible in the analysed data. Nevertheless, impacts or effects on the benthic community of for example bottom trawling cannot be excluded, although and because it was not an object of the present study. In general, the causes for the fluctuations can be manifold and variable, especially in the transitional area of the southern Baltic Sea (ZETTLER et al. 2017).

4.3.3 Long-term trends

Long-term data sets are crucial in assessing the state of the marine system and its ecological processes to disentangle human-induced and natural changes, short-term fluctuations and long-term trends (WASMUND & ZETTLER 2023). As it is not possible to present all long-term developments in diagrams, we change the example of a selected station every year. This year, **station K4 (Arkona Basin)** will be analysed as an example in order to present a comprehensive long-term data series. Here, long-term data of more than 40 years are available. The station in the Arkona

Basin (about 45 m deep) is characterised abiotically by a generally low oxygen content and relatively high salinity values. The number of species is generally low, but stable. It fluctuated on average between 10 and 20 species, with a few exceptions upwards and downwards (Fig. 24). In the last 20 years, a significant decline in diversity has only been observed in a few years (e.g. 2000, 2005, 2013), but this is only partly related to periods of low oxygen levels (see also Fig. 16). In total, more than 66 macrozoobenthic species have been detected over the past 4 decades. Interestingly, the species numbers in the 1980s to mid-1990s were lower than in the following decades. This is probably due to the fact that the method was changed: Since the mid-1990s, we also use a dredge to determine species richness. In general, no total community collapses have been observed in this area in recent decades. Nevertheless, in all measured biotic parameters (taxonomy, abundance and biomass), partly significant changes can be observed over the years (Fig. 24, Fig. 25, Fig. 26).

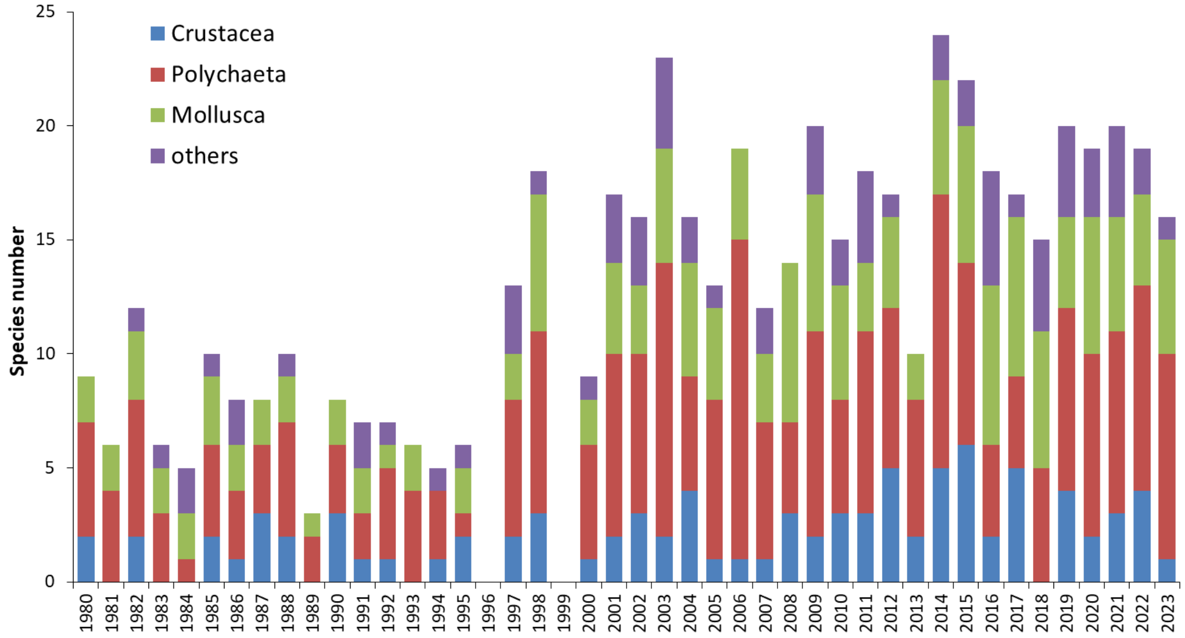


Fig. 24: Long-term development of species number of macrozoobenthic taxa in the Arkona Basin (K4), 1980 - 2023. No data are available for 1996 and 1999.

From 1980 to about the mid-2000s, a continuous increase in species diversity was observed (Fig. 24). Since then, species numbers have levelled off around a very high value (about 45 species). At least in terms of diversity, the crustaceans have diversified over the years. During the last decades two regime shifts for phytoplankton, zooplankton, zoobenthos and fish could be observed in the Baltic Sea (see WASMUND & ZETTLER 2023).

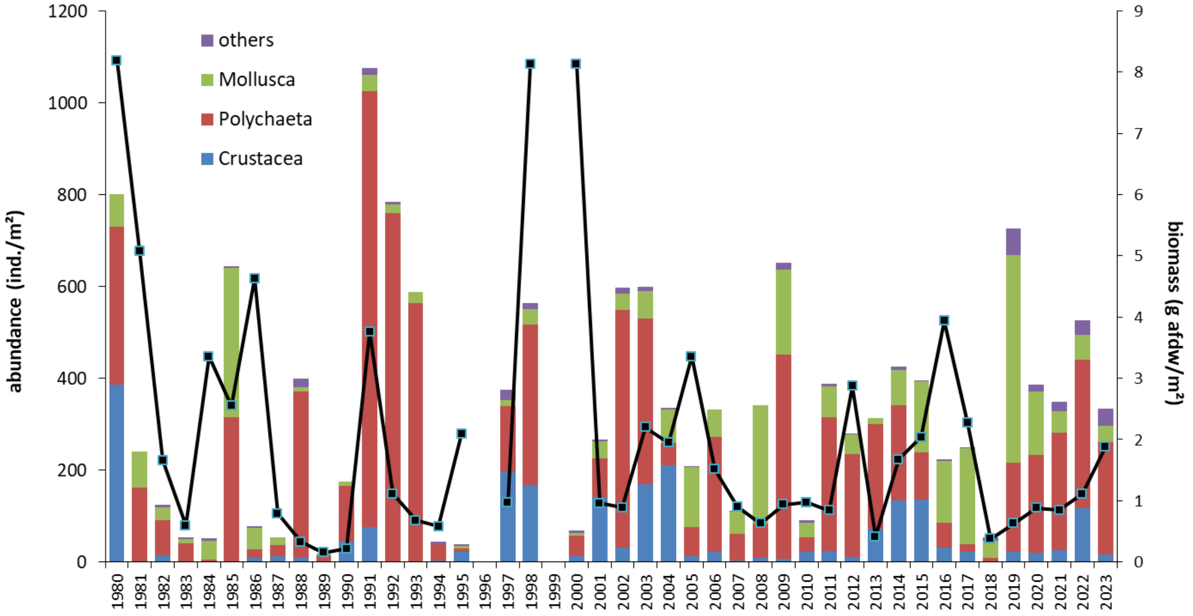


Fig. 25: Long term development of abundance and biomass of macrozoobenthic taxa in the Arkona Basin (K4), 1980 - 2023. Columns show the abundance; the bold line shows the biomass (ash free dry weight, afdw). No data are available for 1996 and 1999.

In some years polychaetes and crustaceans were the dominant taxa (Fig. 25). While the proportion of crustaceans has declined in recent years, molluscs and polychaetes are flourishing. What is striking is the virtual collapse in 2018, when both abundance and biomass showed a significant drop. Similar developments were also observed in the 1980s. On the one hand, this can be explained by the patchiness of the distribution of organisms on the sea floor: The random inclusion of larger quantities and larger organisms influences abundance and biomass by chance. On the other hand, it is surprising that the diversity of species and the population sizes of the predominant species have remained relatively constant over the decades. Species that occur again and again are *Arctica islandica*, *Macoma balthica*, *Bylgides sarsi*, *Scoloplos armiger* and *Diastylis rathkei*.

As an example the development of the cumacean *Diastylis rathkei* is shown (Fig. 26). In some years, the population reached high abundance peaks, which also influenced the total abundance at this station. As far as biomass is concerned, the contribution of *D. rathkei* is quite low. Here, the species *Macoma balthica* and *Arctica islandica* in particular can have a much greater influence on the total biomass (e.g. Fig. 27). The fluctuations of these species of course have an impact on the total biomass at the station and are mostly reflected by the peaks in Fig. 25.

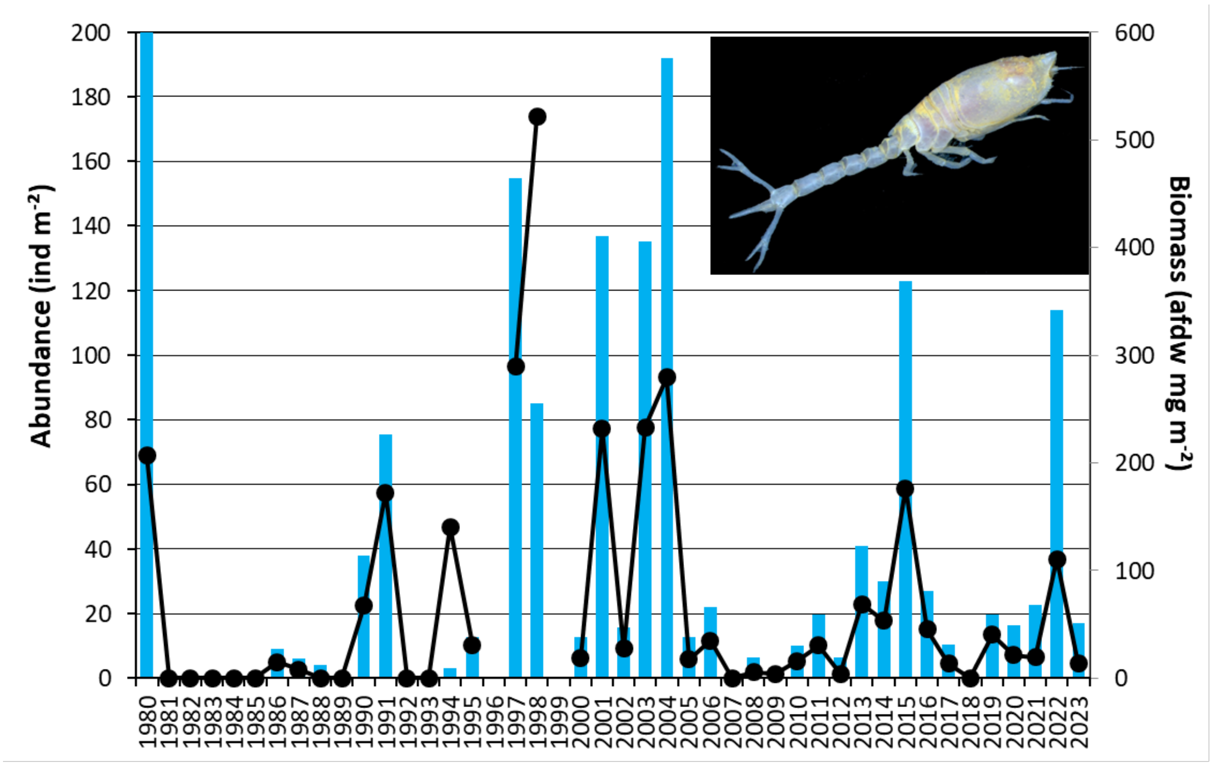


Fig. 26: Long-term development of the abundance (column) and biomass (line) of the cumacean Diastylis rathkei *in the Arkona Basin (K4), 1980 - 2023 (samples taken every autumn). No data available for 1996 and 1999.*

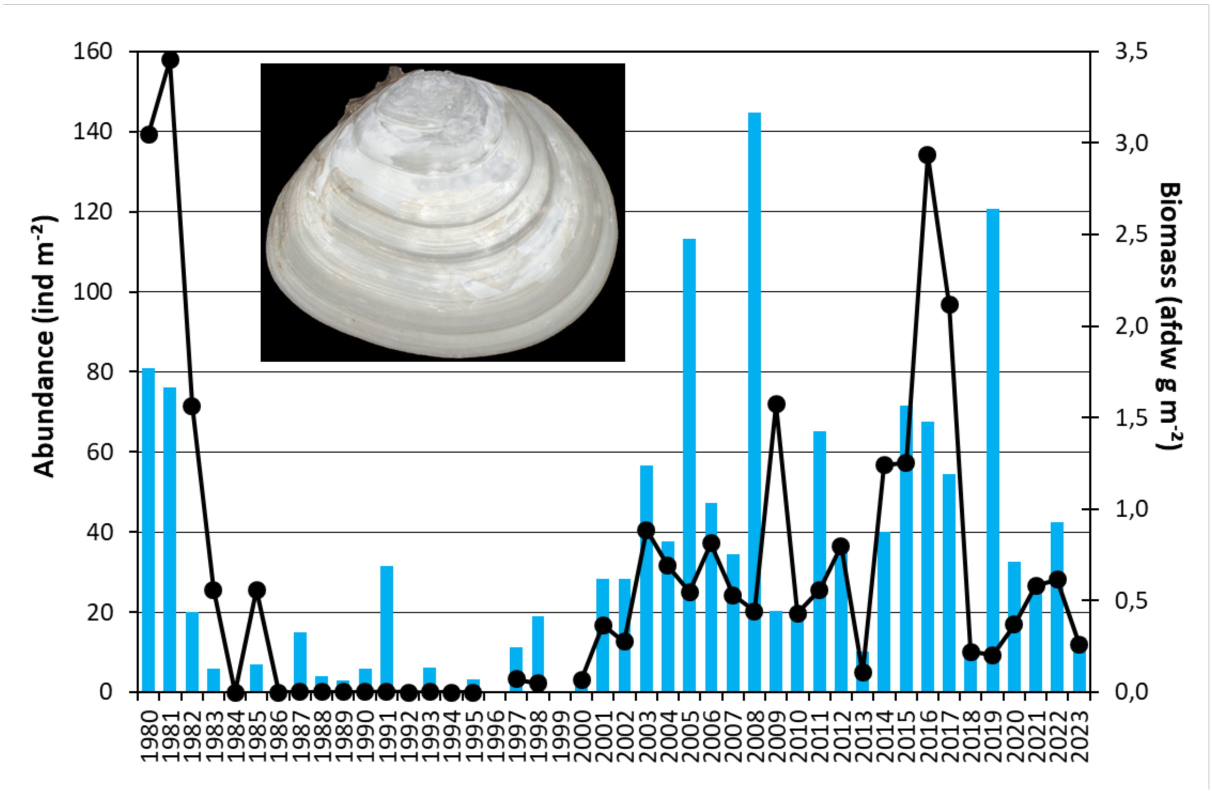


Fig. 27: Long-term development of the abundance (column) and biomass (line) of the bivalve Macoma balthica *in the Arkona Basin (K4), 1980 - 2023 (samples taken every autumn). No data available for 1996 and 1999.*

4.3.4 Red List

This section refers to the Red List of bottom-dwelling invertebrates by Rachor et al. (2013). Of a total of 136 species in 2023, 19 are classed as threatened (1, 2, 3, G) (Fig. 28, Table Appendix 3). Two species are classed as being near threatened. One species is categorised as extremely rare. Currently, 75 species are classed as being of least concern. Data are deficient for 19 species, and 22 taxa on the Red List were not evaluated in the Red List. The anthozoan *Halcampa duodecimcirrata* is critically endangered. It was detected in the Arkona Basin (K4) in very low densities. We observed specimens of *Arctica islandica* (ocean quahog; category 3, vulnerable) at western stations (N3 to OM18) and in the deeper Arkona Basin (K4) at various levels of abundance. Montagu's Astarte (*Astarte montagui*) occurred in the Kiel Bight (N3). Category G of the Red List (probably vulnerable) includes species that cannot be assigned to category 1, 2 or 3 above, but which - based on current knowledge - are assumed to be endangered. They are considered to be at risk (uncategorized). The 16 species observed in 2023 were distributed across almost all sea areas: 13 species in Kiel Bight (N3), 6 at the Fehmarnbelt (N1), 3 at the Mecklenburg Bay (OM18), 2 at the Darss Sill (K8), 2 in Arkona Basin (K4) and 2 in northern Pomeranian Bay (K3). Examples are the polychaetes *Fabriciola baltica, Nereimyra punctata, Platynereis dumerilii, Scalibregma inflatum* and *Travisia forbesii*. Others are the gastropods *Aporrhais pespelecani, Neptunea antiqua* and *Tritia reticulata*, which occur in the western part of the investigation area (N3 and/or N1).

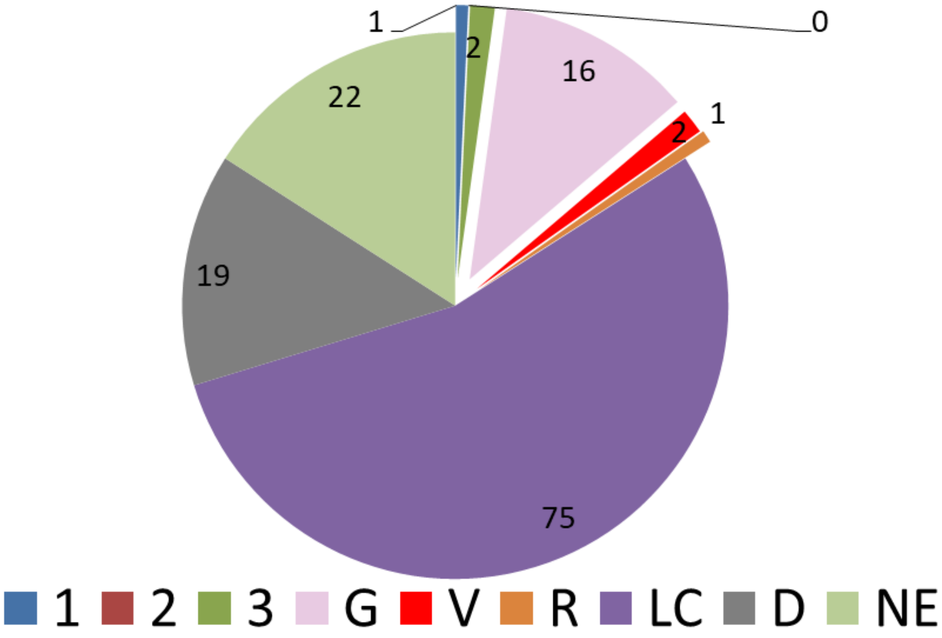


Fig. 28: Distribution of red list categories (Rachor et al. 2013) in relation to macrozoobenthos in autumn 2023 (1=critically endangered, 2=endangered, 3=vulnerable, G=probably vulnerable, V=near threatened, R=extremely rare, LC=least concern, D=data deficient, NE=not evaluated); the given values are the absolute species numbers.

In general, the number of potentially occurring red listed species at the monitoring stations is decreasing systematically along the salinity gradient from west to east (Table Appendix 3). The strong salinity gradient and its effect on the distribution of red listed marine species are clearly visible. No species of the Helcom Red List were found (Helcom 2013b).

4.3.5 Benthic Quality Index (BQI)

A monitoring network was initially established as a follow-up of the coming into force of the Helsinki Convention in 1979/1980. The original aim of the monitoring of the marine environment conducted by the bordering countries was the determination of long-term changes caused by human influences (initially mainly eutrophication and later on also climate change) based on selected environmental parameters and biological components at selected stations (at least one per Baltic Sea basin). Due to increasing pressure on the aquatic environment, the European Union adopted several directives (e.g. HD, WFD and MSFD) that include the obligation to monitor environmental changes and states. However, the directives pursue very differing goals and require much more effort to implement. Consequently, our monitoring strategies have evolved over time. Nevertheless, it has to be stressed, that the monitoring performed within the framework of HELCOM in no way meets the requirements of the European directives. Neither do the few stations cover all the different habitat types according to MSFD (broad habitat types, BHT, EU-Kommissionsbeschluss 2017/848/EU 2017). Nevertheless, they are a valuable tool for detecting long-term changes and their causal relationships, e.g. for gradual processes such as eutrophication and climate change.

With regard to the BQI (indicator to be used within the MFSD descriptor D6C5 = condition of the benthic habitat), it also has to be highlighted that conceptually many stations per BHT are required to reach a sound assessment result. BQI-values at individual stations should be considered with caution as they are subject to natural variability. However, significant changes over time may nevertheless be visible. Consequently, the present study shows how such an assessment of the benthic component would look like and whether it could be usefully applied. For this purpose, we applied the Benthic Quality Index in an adapted form to the data of our eight long-term stations, initially from 2006 to 2021 (Kremp et al. 2021), now extended to include the data from 2022 to 2023. The BQI is used for basin-wide assessments within HELCOM and also serves as an additional German indicator (with some specific adaptations, BMUV 2024).

We are aware that the stationwise approach as presented here is unusual, as HELCOM monitoring is not designed to assess habitat types via BQI. Nevertheless, with this method we can show quite clearly, how the stations develop over longer periods and where stable or where rather variable conditions prevail.

The eight stations (N3, N1M2, OM18, K8, K4, K3, and OM160) were sampled once a year for 18 years (2006 to 2023). With the exception of 2022, in which two stations could not be sampled due to poor weather conditions, three hauls were always carried out. All data were used to calculate the Benthic Quality Index (BQI). In total, we have 142 samples at the stations, each with 3 replicates (3 hauls), i.e. a total of 426 individual hauls.

The BQI was calculated using the formula for the BQI according to Leonardsson et al., 2009 (equation 1).

Equation 1:

$$BQI = \left(\sum_{i=1}^{S_{classified}} \left(\frac{N_i}{N_{classified}} \times ES_{50_{0,05i}} \right) \right) \times log_{10}(S+1) \times \left(\frac{N_{total}}{N_{total}+5} \right)$$

Where S is the number of taxa, N_i the abundance of taxon i, $N_{classified}$ the number of individuels with a sensitivity value and N_{total} the sum of all individuals on the sampled plot. The $ES50$ corresponds to the expected number of taxa from 50 randomly selected individuals of a sampling plot. The $ES50_{0,05}$ is the sensitivity value for taxon i according to SCHIELE et al. (2016). It corresponds to the lower 5 % percentile of all $ES50$ values determined for this taxon (ROSENBERG et al., 2004).

In case of spatial, temporal or methodological disparities between samples, HELCOM (2023) recommends bootstrapping. This is used as a safety method to assign a lower value to values with a high uncertainty (CARSTENSEN, 2007; LEONARDSSON et al., 2009). However, since the samples were taken from the same sites every autumn, always with three hauls each, no spatial, temporal or methodological inconsistencies are to be expected. The bootstrapping procedure was therefore not carried out.

The sensitivity value is calculated from the abundance of species at a site and is based on the assumption that sensitive species mainly occur at undisturbed sites with a high diversity, whereas tolerant species mainly dominate at disturbed sites with a low diversity (ROSENBERG et al., 2004). Due to differences in community composition and sensitivity of individual taxa along different natural gradients, the sensitivity values to be used are not the same for the whole Baltic Sea. Therefore, SCHIELE et al. (2016) divided the Baltic Sea into 19 Ecological Indicator Groups (EIG) based on the factors salinity, water depth and sampling method used. They calculated the sensitivity value per taxon ($ES50_{0,05}$) for each subgroup. Five of the 19 subgroups are relevant for the German Baltic Sea (EIG2 to EIG6).

For all years, each station was assessed as "good" or "poor" using the calculated BQI values and the associated threshold values for the specific EIG (BLANO 2024, SCHAUB et al., 2024). For each station, the proportion of hauls per station that had received the rating "good" over the entire sampling period was then calculated (EcoQ status "good" in %, see Table 10). According to HELCOM (2023), an area is classified as “poor” if more than 20 % of the hauls per station are rated as “poor”. Therefore, stations that had received at least 80 % EcoQ status of "good" over the 18 years were rated "good" overall. Stations with less than 80 % "good" status were rated "poor" (overall rating, see Table 10).

Table 10: For each station, the mean BQI (Benthic Quality Index; median; per haul station over 18 years), the mean normalised BQI (median; per haul station over 18 years; normalised over the threshold of the respective EIG), the EIG (Ecological Indicator Group) used, the EcoQ status "good" (percentage of haul stations with EcoQ (Ecological Quality) status of "good") and the overall assessment (stations were assessed as "poor" if less than 80% of the haul stations had EcoQ status "good") over the entire sampling period; FixSal (modelled mean water depth and salinity).

Station	BQI_FixSal (Median)	BQI_FixSal normalised (Median)	Used EIG FixSal	EcoQ-Status „good" (%) FixSal	Rating
N3	10,44	1,31	EIG 2	98,18	good
N1	7,32	0,77	EIG 3	1,96	poor
M2	5,13	0,54	EIG 3	0,00	poor
OM18	8,09	1,01	EIG 2	55,56	poor
K8	6,42	1,23	EIG 4b	94,44	good
K4	3,78	0,72	EIG 4b	3,70	poor
K3	4,40	1,25	EIG 5	100,00	good
OM160	3,93	1,12	EIG 5	83,33	good

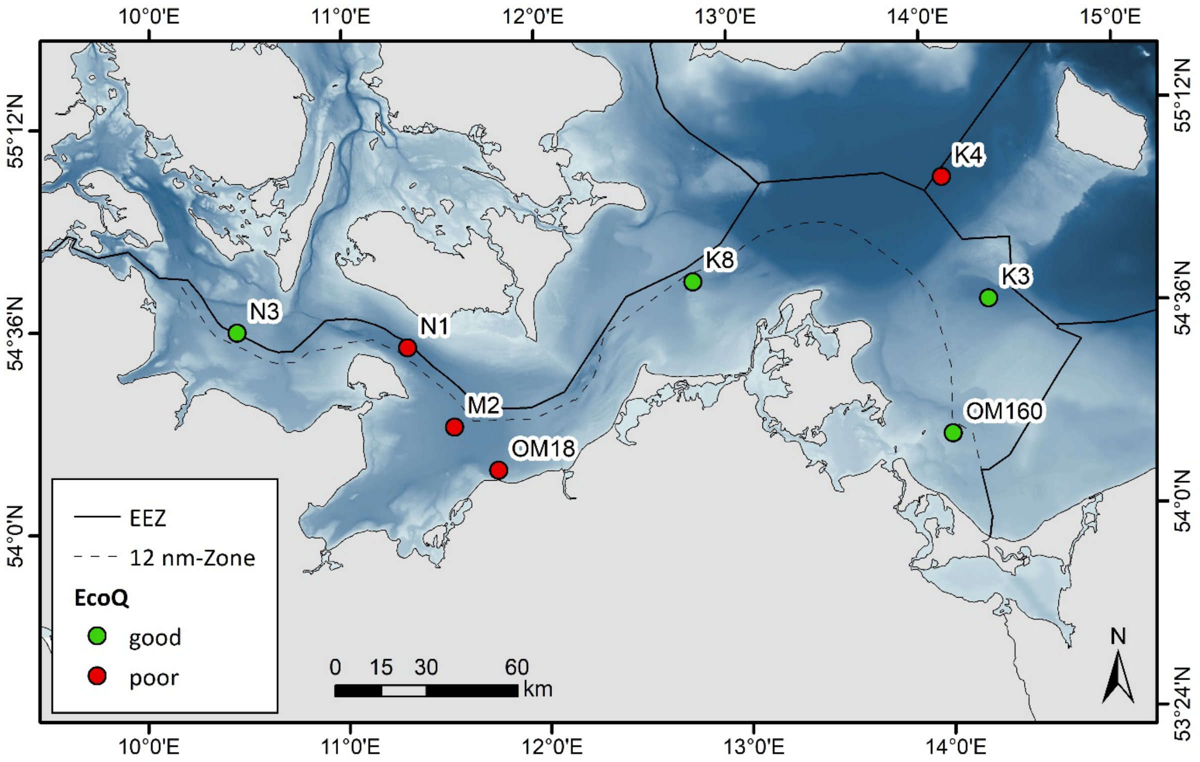


Fig. 29: Locations and EcoQ (Ecological Quality) assessment of the eight stations studied with FixSal (modelled mean water depth and salinity), averaged over 18 years (2006 - 2023); EEZ = exclusive economic zone; 12 nm zone = twelve nautical mile zone; projection: LAEA - ETRS89; background: Bathymetrie BSH (2012).

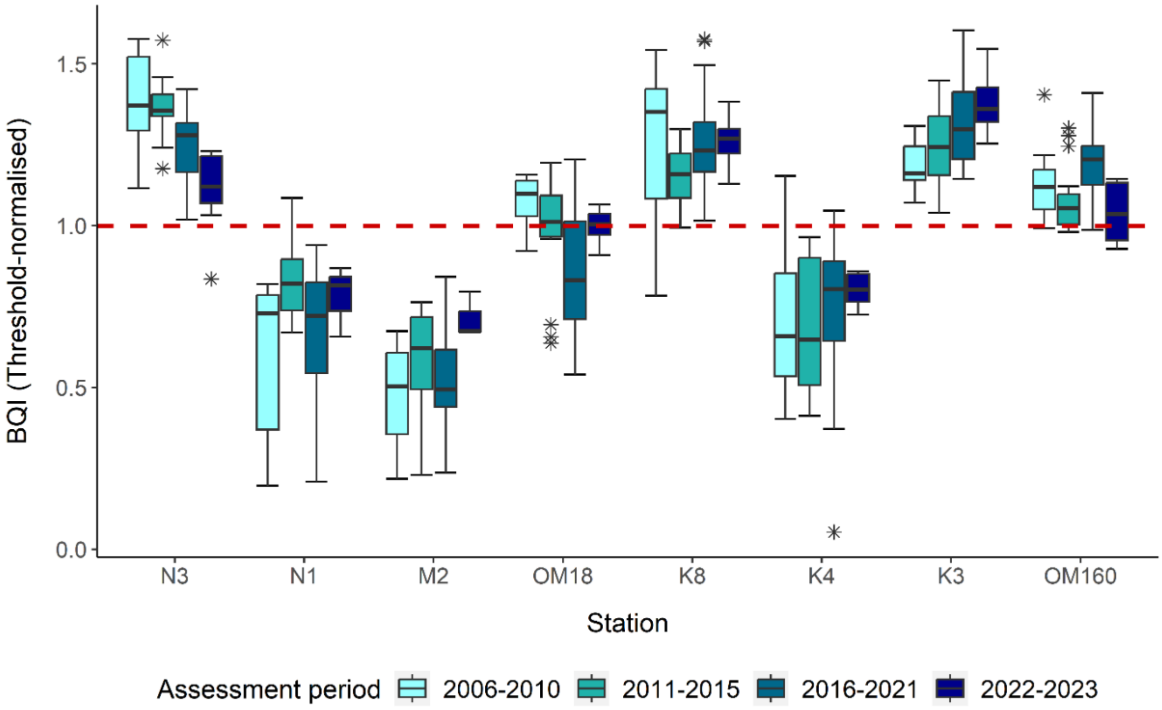


Fig. 30: Boxplots of the normalised BQI (Benthic Quality Index) values per station for four different assessment periods (2006 – 2010, 2011 – 2015, 2016 – 2021, 2022 – 2023) according to FixSal (modelled mean water depth and salinity); the BQI was normalised by the threshold value for the respective EIG (Ecological Indicator Group; BMUV 2024).

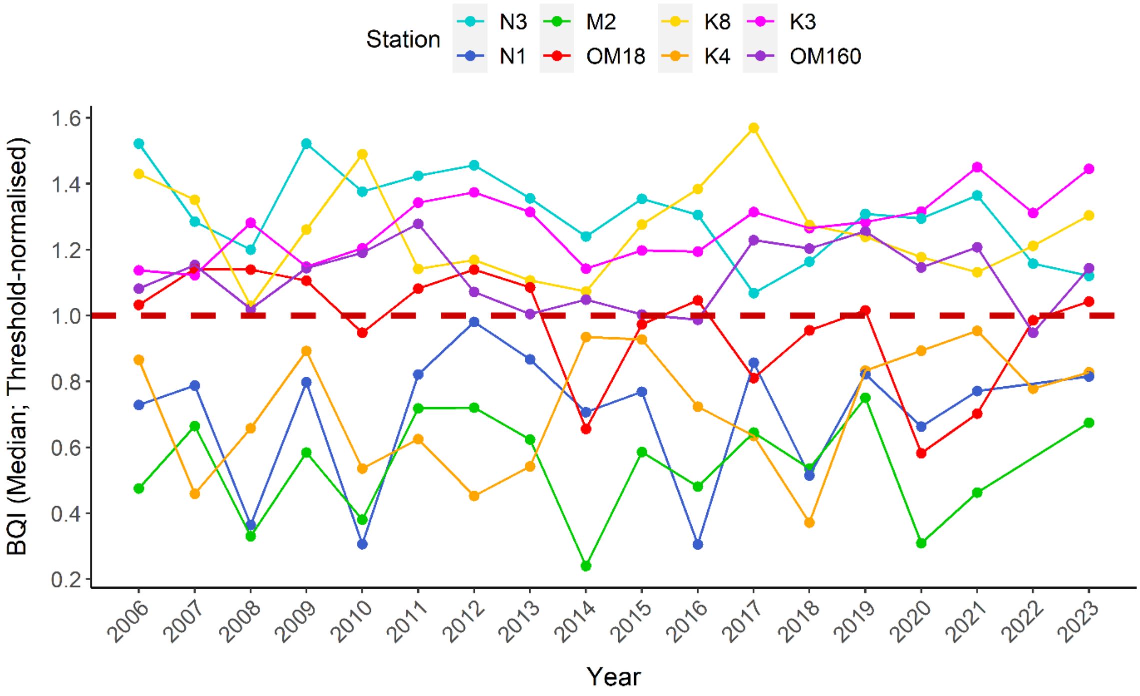


Fig. 31: The normalised BQI (Benthic Quality Index) value for each station (median of the three hauls) over time (2006 to 2023) according to FixSal (modelled mean water depth and salinity); the BQI was normalised by the threshold value for the respective EIG (Ecological Indicator Group; BLANO 2024); the red line marks the boundary between a "good" (› 1) and "poor" (‹ 1) ecological status.

In summary, the stations in the Kiel Bay (N3), Darss Sill (K8), northern Pomeranian Bay (K3) and Pomeranian Bay (OM160) always show a "good" ecological status (Fig. 29, Fig. 30, Fig. 31). The Arkona Basin (K4) and the Mecklenburg Bay (M2) were more than 50 % in a “poor” condition (Table 10, Fig. 30, Fig. 31). Fehmarnbelt (N1) and the southern Mecklenburg Bay (OM18) were more than 70 % in "good" condition, but also more than 20 % in "poor" condition and are therefore assessed as "poor" according to threshold rules.

The map of the BHT assessment of the German Baltic Sea, which was created in our working group and leads to GES threshold values for the entire German Baltic Sea and is not the subject of this study, shows a high degree of agreement with the station values presented here (BMUV 2024, p. 173-174). The circalittoral mud of the Bay of Kiel, Mecklenburg Bay and Arkona Sea do not achieve good environmental status. Only the infralittoral sands of the Pomeranian Bay and with some exceptions also the circalittoral sands of the Arkona Sea can be described as good. The main reason for this is likely to be the irregularly recurring oxygen deficiency events in the deeper basins of the southern Baltic Sea and the resulting adverse effects on living organisms.

4.3.6 Non-indigenous species (NIS)

The role of NIS in the open Baltic Sea is negligible (Zettler et al. 2014, 2018). Ten species were observed at our eight monitoring stations in 2023 (Table Appendix 3). *Amphibalanus improvisus* (bay barnacle) and *Mya arenaria* (soft-shell clam) have been present in the Baltic region for so long now that they barely still qualify as invasive species (Zettler & Alf 2021, Meng et al. 2024). The spionid polychaete *Marenzelleria neglecta* finds suitable habitat conditions in coastal waters. We found this species at the Oderbank (OM160), normally the sister species (M. viridis) is more common at this station. In addition, for the polychaetes *Alitta succinea* and *Aphelochaeta marioni*, it is not clear whether they are neozoic or cryptic native species (Lackschewitz et al. 2022). The tunicates *Molgula manhattensis* and the decapod *Rhithropanopeus harrisii*, both originally from North America, were found in the Kiel Bight (N3), the Darss Sill (K8) and the Pomeranian Bight (OM160) respectively. None of these observed NIS was recorded for the first time; all have been established for years. The amphipod *Grandidiriella japonica*, which was first observed in the Kiel Bay (N3) last year, was detected there again this year. This species, originally distributed in the western Pacific, first appeared in the Baltic Sea in 2015 (see Zettler & Zettler 2017) and has established itself in Kiel and Mecklenburg Bight as well as in several estuaries. The bivalve *Ensis leei*, a North American species, was recorded for the first time on the Darss Sill (K8). It is normally (albeit sparsely) more common in the western part of the Baltic Sea (Zettler & Alf 2021). Since 2019 the Japanese cumacean *Nippoleucon hinumensis* is known for the Baltic Sea (Schüler et al. 2020). In addition to several detections that we have made in other campaigns throughout the German Baltic Sea (especially in estuaries), we found it for the first time this year during monitoring sampling in the Kiel Bay (N3). Over the last ten years, we have found a total of 16 non-indigenous species (NIS) at our eight monitoring stations with 7 new arrivals (Fig. 32). The long-term trend over the last 10 years of arrival was 0,8 NIS per year (the first year acts as the status quo). In comparison to Denmark (see Staehr et al. 2020) both the total number and the rate of arrival is similar. For Danish marine waters and estuaries (North and Baltic Sea together) the authors present 16 (+6 species outside the monitoring programme) marine benthic invertebrates species (what is definitely not complete). However, if you only look at the Baltic and Belt Sea itself, around 1 to 7 non-native species are detected each year (STAEHR et al. 2020). The calculated Danish NIS arrival trend is around 0,9, but it is not really easy to extract from the given data. In German inner-coastal waters, the introduction rates are 0,2 to 1,2 NIS per year (e.g. ZETTLER & ZETTLER 2024), which is more or less in the same range as we found in the present study.

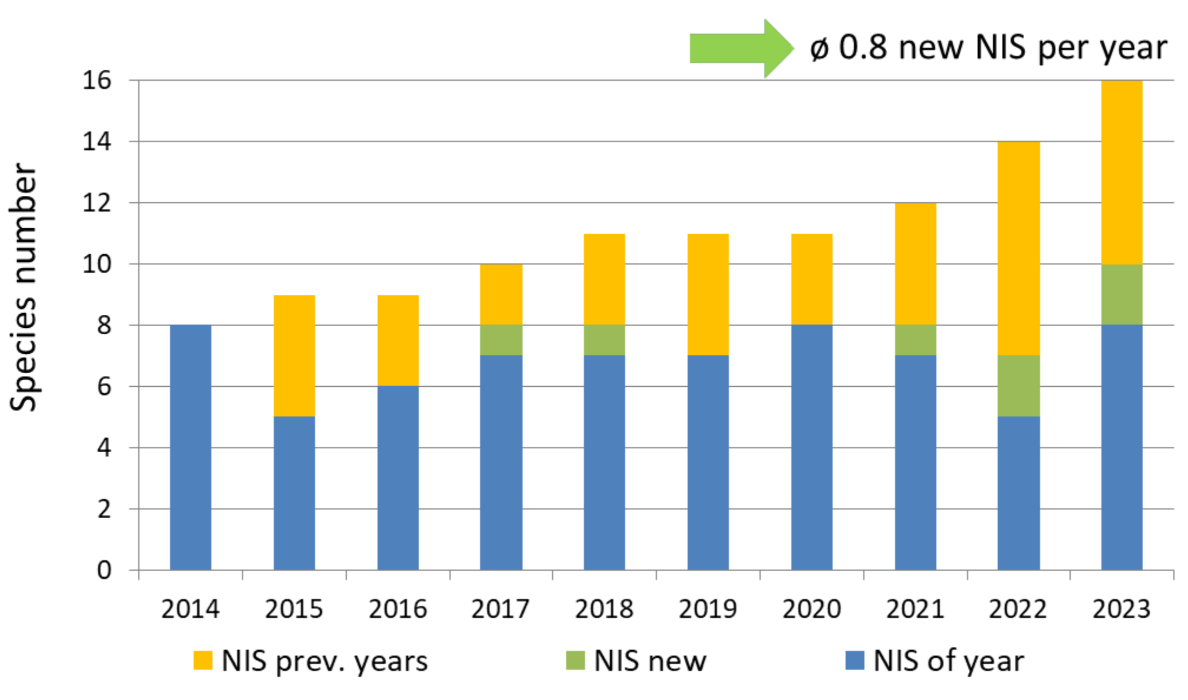


Fig. 32: Monitoring of the non-indigenous species (NIS) at eight monitoringstations from 2014 to 2023. Blue=NIS-species of the respective year without the new species, green=new discoveries, orange=species known from previous years but not found this year. The year 2014 acts as status quo. The mean NIS per year are calculated from the following years.

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Appendix

Table Appendix 1: List of phytoplankton-taxa recorded in 2023 on five monitoring cruises. Biomass rank and mean biomass per station, as well as and presence of taxa (X) on cruises.

Taxon	rank	BM/St.	TF0223	TF0323	TF0523	TF0823	TF1123
Rhizosolenia delicatula	1	134.54	X	X	X	X	X
Cerataulina bergonii	2	75.63	X			X	X
Mesodinium rubrum	3	56.21	X	X	X	X	X
Rhizosolenia fragilissima	4	39.18	X			X	X
Proboscia alata	5	33.62	X			X	X
Rhizosolenia semispina	6	29.37	X	X			X
Tripos muelleri	7	16.62	X	X	X	X	X
Thalassiosira	8	14.35	X			X	X
Polykrikos schwartzii	9	10.66				X	X
Pseudosolenia calcar-avis	10	10.35	X			X	X
Heterocapsa rotundata	11	9.21	X	X	X	X	X
Ebria tripartita	12	8.74	X	X	X	X	X
Gymnodiniales	13	7.82	X	X	X	X	X
Cymbomonas tetramitiformis	14	7.17		X		X	
Teleaulax	15	6.95	X	X	X	X	X
Nodularia spumigena	16	6.66				X	
Rhizosolenia flaccida	17	6.64	X	X		X	X
Ditylum brightwellii	18	6.61	X				X
Prymnesiales	19	5.29	X		X	X	X
Aphanizomenon	20	5.00	X	X	X	X	X
Flagellates	21	4.36	X	X	X	X	X
Pyramimonas	22	4.24	X	X	X	X	X
Gymnodinium	23	3.75	X	X	X	X	X
Unicell spp.	24	3.73	X	X	X	X	X
Prorocentrum micans	25	3.56	X			X	X
Coscinodiscus commutatus	26	3.51					X
Gyrodinium spirale	27	3.07	X	X		X	X
Plagioselmis prolonga	28	3.01	X	X	X	X	X
Eutreptiella	29	2.94	X	X	X	X	X
Tripos fusus	30	2.81	X	X		X	X
Telonema	31	2.41	X	X	X	X	X
Centrales	32	2.31		X		X	X

Prorocentrum cordatum	33	2.28	X	X		X	X
Diplopsalis spp. CPX	34	2.17	X			X	X
Octactis speculum NK	35	1.87			X	X	X
Karlodinium veneficum cf.	36	1.81				X	X
Skeletonema marinoi	37	1.71	X	X		X	X
Protoperidinium	38	1.65	X	X		X	X
Peridiniales	39	1.55	X	X	X	X	X
Actinocyclus	40	1.51	X	X	X		X
Octactis speculum	41	1.48	X	X			X
Micracanthodinium	42	1.32				X	X
Tripos lineatus	43	1.22	X				X
Leucocryptos marina	44	1.16	X	X	X	X	X
Coscinodiscus radiatus	45	1.13	X	X			X
Chaetoceros castracanei	46	1.12	X	X	X		X
Laboea strobila	47	1.12	X	X		X	X
Katablepharis remigera	48	1.07				X	X
Hemiselmis	49	1.07	X	X	X		X
Pseudopedinella	50	0.93	X	X	X	X	X
Ethmodiscus punctiger	51	0.89	X				
Scrippsiella GRP	52	0.85				X	X
Rhizosolenia setigera	53	0.82					X
Coscinodiscus granii	54	0.78					X
Chaetoceros danicus	55	0.75	X	X	X	X	X
Pseudanabaena limnetica cf.	56	0.72				X	
Dinophysis norvegica	57	0.71	X	X	X		X
Peridiniella danica	58	0.70		X	X	X	X
Alexandrium pseudogonyaulax	59	0.69				X	
Octactis speculum NK cf.	60	0.62				X	
Protoperidinium divergens	61	0.54				X	X
Heterosigma cf.	62	0.50	X				X
Synedra nitzschioides f. nitzschioides	63	0.48	X	X	X	X	X
Dinophysis acuminata	64	0.47	X	X	X	X	X
Apedinella radians	65	0.42		X			
Katodinium glaucum	66	0.34	X	X	X	X	X
Tripos furca	67	0.34	X				X
Pseudanabaena limnetica	68	0.32	X	X		X	X

Gymnodinium corollarium cf.	69	0.31		X	X		
Chaetoceros	70	0.28		X		X	X
Dolichospermum	71	0.27				X	
Katablepharis	72	0.27	X	X	X	X	X
Pseudochattonella farcimen	73	0.25	X	X			X
Chroococcales	74	0.24			X	X	X
Kryptoperidinium triquetrum	75	0.23	X	X	X	X	X
Chaetoceros debilis	76	0.22		X			
Thalassiosira gravida	77	0.21					X
Navicula	78	0.20		X	X		
Choanoflagellatea	79	0.19	X	X	X	X	X
Rhizosolenia setigera f. pungens	80	0.14				X	X
Tripos longipes	81	0.13		X			
Scrippsiella GRP cf.	82	0.13				X	
Pterosperma	83	0.12				X	
Snowella	84	0.12	X	X	X	X	X
Roperia tesselata	85	0.12					X
Cylindrotheca closterium	86	0.11	X	X		X	X
Amphidinium crassum	87	0.10				X	
Chaetoceros convolutus	88	0.10					X
Protoperidinium pellucidum	89	0.10	X				X
Thalassiosira eccentrica	90	0.09					X
Gonyaulax	91	0.08				X	
Karenia mikimotoi cf.	92	0.08					X
Heterocapsa triquetra cf.	93	0.07	X				
Dinophyceae	94	0.07				X	
Micracanthodinium cf.	95	0.07				X	
Leptocylindrus minimus	96	0.07				X	X
Dinobryon faculiferum	97	0.07			X	X	X
Nitzschia longissima	98	0.06	X			X	X
Trachelomonas	99	0.06			X		X
Binuclearia lauterbornii	100	0.06	X	X	X		X
Dinobryon	101	0.05			X	X	
Akashiwo sanguinea	102	0.04					
Chaetoceros similis	103	0.04	X	X	X		X
Gyrodinium flagellare	104	0.04	X		X		X
Rhizosolenia minima	105	0.04				X	

Azadinium cf.	106	0.04				X	
Preperidinium meunieri	107	0.04				X	
Cyanodictyon planctonicum	108	0.03	X		X	X	
Chaetoceros decipiens cf.	109	0.03		X			
Apocalathium malmogiense cf.	110	0.03		X			
Miraltia throndsenii	111	0.03				X	
Leptocylindrus minimus cf.	112	0.00					
Lessardia elongata cf.	113	0.03					X
Cyclotella	114	0.03			X	X	X
Oxytoxum gracile cf.	115	0.02					X
Thalassiosira nordenskioeldii	116	0.02		X			
Amphidinium sphenoides	117	0.02	X	X			
Chaetoceros decipiens	118	0.02		X			
Chaetoceros septentrionalis	119	0.02		X			
Peridiniella catenata	120	0.02	X				
Chaetoceros socialis	121	0.02				X	X
Leptocylindrus danicus	122	0.01					X
Aphanothece	123	0.01				X	
Lennoxia faveolata	124	0.01		X			X
Amphidinium cf.	125	0.01					X
Woronichinia	126	0.01	X			X	X
Phalacroma rotundatum	127	0.01					X
Romeria	128	0.01				X	
Dinobryon balticum	129	0.01			X	X	
Micracanthodinium claytonii	130	0.01					X
Pennales	131	0.01		X			
Cyanodictyon	132	0.01				X	
Protoperidinium bipes	133	0.01				X	X
Pseudo-nitzschia	134	0.00	X				X
Torodinium robustum	135	0.00					X
Dinobryon borgei	136	0.00			X		
Amphidinium longum	137	0.00				X	
Nitzschia paleacea	138	0.00				X	
Oocystis	139	0.00		X			
Pseudo-nitzschia delicatissima GRP	140	0.00	X				
Monoraphidium minutum	141	0.00		X			

Table Appendix 2: Seasonal occurrence of taxa found in the investigation area in 2023 with information on original description, taxonomic rank and taxonomic life science identifier according to the Aphia Database (AphiaID) of the world register of marine species (WoRMS).

	rank	AphiaID	Feb	March	May	Aug	Nov
Protozoa							
Tintinnidae Claparède & Lachmann, 1858	Family	183533		o		o	o
Annelida							
Polychaeta - Trochophora	Subphylum		o	o			
Polychaeta Grube, 1850	Subphylum	883	o	o		o	o
Harmothoe spp. Kinberg, 1856	Genus	129491	o	o			
Arthropoda - Crustacea							
Copepoda							
Acartia Dana, 1846	Genus	104108	o	o	o	o	o
Acartia bifilosa Giesbrecht, 1881	Species	345919	o	o	o	o	o
Acartia longiremis Lilljeborg, 1853	Species	346037	o	o	o	o	o
Acartia tonsa Dana, 1849	Species	345943				o	o
Calanus Leach, 1816	Species	104466	o				
Centropages Krøyer, 1849	Genus	104159	o	o	o	o	o
Centropages hamatus Lilljeborg, 1853	Species	104496	o	o	o	o	o
Cyclopoida Burmeister, 1834	Order	1101	o	o			
Eurytemora Giesbrecht, 1881	Genus	104240			o		o
Eurytemora affinis Poppe, 1880	Species	104872		o			
Euterpina acutifrons Dana, 1847	Species	116162				o	o
Harpacticoida G. O. Sars, 1903	Order	1102	o				o
Limnocalanus Sars G.O., 1863	Genus	157673		o			
Microsetella spp. Brady & Robertson, 1873	Genus	115341	o	o	o	o	o
Oithona Baird, 1843	Genus	106485	o	o	o	o	o
Oithona atlantica Farran, 1908	Genus	106642		o			
Oithona similis Claus, 1866	Species	106656	o	o	o	o	o
Paracalanus parvus Claus, 1863	Species	104685	o	o	o	o	o
Pseudocalanus spp. Boeck, 1872	Genus	104165	o	o	o	o	o
Temora Baird, 1850	Genus	104241	o	o	o	o	o
Temora longicornis O.F.Müller, 1785	Species	104878	o	o	o	o	o
Phyllopoda							
Bosmina spp. Baird, 1845	Genus	106265				o	o
Evadne nordmanni Lovén, 1836	Species	106273	o	o	o	o	o
Podon intermedius Lilljeborg, 1853	Species	106276				o	o
Podon leuckartii G. O. Sars, 1862	Species	106277	o	o	o		o
Pleopis polyphemoides (Leuckart,1859)	Species	247981				o	
Penilia avirostris Dana, 1849	Species	106272				o	o

Tab. A2 continued.

	Rang	TSN	Feb	März	Mai	Aug	Nov
other Crustacea							
Balanus spp. Costa, 1778	Genus	106122	o	o		o	o
Carcinus maenas Linnaeus, 1758	Species	107381				o	
Palaemon serratus (Pennant, 1777)	Species	107616				o	
Bryozoa							
Gymnolaemata Allman, 1856	Class	1795	o	o		o	o
Chaetognatha							
Sagittidae Claus and Grobben, 1905	Family	5953	o				
Chordata							
Fritillaria borealis Lohmann, 1896	Species	103375	o	o	o		
Oikopleura dioica Fol 1872	Species	103407	o	o		o	o
Teleostei	Infraclass	293496	o	o	o		
Echinodermata							
Asterias spp. Linnaeus, 1758	Genus	123219				o	
Cnidaria & Ctenophora							
Ctenophora Eschscholtz, 1829	Phylum	1248	o	o	o	o	o
Leptothecata Cornelius, 1992	Order	13552		o		o	
Euphysa aurata Forbes, 1848	Species	117561		o			
Rathkea octopunctata M. Sars, 1835	Species			o			
Phoronida							
Phoronis muelleri Selys-Longchamps, 1903	Species	206663				o	o
Platyhelminthes							
Alaurina spp. Metschnikoff, 1861	Genus	142785	o			o	o
Leptoplanidae Stimpson, 1857	Family	142062					o
Mollusca							
Bivalvia Linnaeus, 1758	Class	105	o	o	o	o	o
Gastropoda Cuvier, 1797	Class	101	o	o	o	o	o
Rotifera							
Synchaeta spp. Ehrenberg, 1832	Genus	134958	o	o	o		o
Keratella cochlearis(Gosse, 1851)	Species	134990	o			o	o
Keratella quadrata O. F. Muller, 1786	Species	134992	o			o	o

*Table Appendix 3: Distribution of macrozoobenthos at six stations in November 2023. In the right column the red list (Rachor et al. 2013) species are indicated (1=critically endangered, 2=endangered, 3=vulnerable, G=probably vulnerable, V=near threatened, R=extremely rare, D=data deficient, *=least concern, ne=not evaluated). Neozoan species are indicated in yellow.*

Taxa	N3	N1	M2	OM18	K8	K4	K3	OM160	RL
Amphipoda									
Corophium volutator								1	*
Crassicorophium crassicorne					1				*
Dexamine spinosa	1								*
Gammarus oceanicus					1				*
Gammarus salinus					1		1	1	*
Gammarus zaddachi							1		*
Grandidierella japonica	1								ne
Megamphopus cornutus	1								*
Metopa pusilla	1								*
Microdeutopus gryllotalpa					1			1	*
Monocorophium insidiosum	1								*
Anthozoa									
Halcampa duodecimcirrata						1			1
Metridium senile		1							G
Sagartia sp.		1							ne
Arachnida									
Halacaridae	1								ne
Ascidiacea									
Dendrodoa grossularia	1								V
Molgula manhattensis	1								D
Bivalvia									
Abra alba		1							*
Arctica islandica	1	1	1	1		1			3
Astarte borealis	1	1			1	1			G
Astarte elliptica	1			1		1			G
Astarte montagui	1								3
Cerastoderma glaucum								1	*
Ensis leei					1				ne
Hiatella arctica	1								*
Kurtiella bidentata	1	1	1	1					*
Macoma balthica	1			1	1	1	1	1	*
Musculus discors	1								G
Musculus subpictus	1								G
Mya arenaria			1	1	1		1	1	*
Mytilus edulis	1	1		1	1		1	1	*
Parvicardium pinnulatum	1	1	1	1	1				D
Phaxas pellucidus				1					*
Spisula subtruncata	1	1		1					G
Varicorbula gibba	1			1	1				*
Bryozoa									
Alcyonidium diaphanum	1								*
Alcyonidium polyoum	1				1				D
Amathia sp.	1								ne
Callopora lineata	1				1				*

Taxa	N3	N1	M2	OM18	K8	K4	K3	OM160	RL
Cribrilina punctata	1	1							*
Einhornia crustulenta	1	1		1				1	*
Electra pilosa	1	1			1				*
Escharella immersa	1								*
Eucratea loricata	1				1		1		V
Flustra foliacea	1								*
Walkeria uva	1	1							*
Cirripedia									
Amphibalanus improvisus								1	ne
Cumacea									
Diastylis rathkei	1	1	1	1		1	1		*
Nippoleucon hinumensis	1								ne
Decapoda									
Carcinus maenas					1				*
Crangon crangon	1	1		1	1		1	1	*
Rhithropanopeus harrisii					1			1	ne
Echinodermata									
Asterias rubens	1		1	1	1			1	*
Echinocyamus pusillus	1								G
Ophiura albida	1	1	1						*
Psammechinus miliaris	1								*
Entoprocta									
Barentsia sp.	1								ne
Gastropoda									
Ancula gibbosa	1								*
Aporrhais pespelecani	1	1							G
Brachystomia scalaris					1				*
Neptunea antiqua	1								G
Onchidoris muricata	1								*
Parthenina interstincta	1								*
Peringia ulvae	1	1	1	1	1	1	1	1	*
Philine punctata		1		1					*
Philine quadripartita	1								*
Retusa obtusa		1	1						*
Retusa truncatula	1			1	1				*
Tritia reticulata	1	1							G
Hydrozoa									
Filellum serpens	1								D
Hartlaubella gelatinosa	1				1		1		D
Hydractinia echinata	1	1							*
Sertularia cupressina		1							G
Isopoda									
Cyathura carinata								1	D
Jaera albifrons					1		1	1	*
Mysida									
Mysis mixta					1		1		ne
Neomysis integer							1		ne
Praunus flexuosus								1	ne
Nemertea									

Taxa	N3	N1	M2	OM18	K8	K4	K3	OM160	RL
Lineus ruber					1				ne
Lineus viridis	1				1				ne
Malacobdella grossa		1	1	1					ne
Nemertea	1			1					ne
Oligochaeta									
Tubificinae	1	1			1		1	1	ne
Tubificoides benedii					1		1	1	*
Phoronida									
Phoronis sp.	1	1	1	1					ne
Platyhelminthes									
Platyhelminthes					1			1	ne
Polychaeta									
Alitta succinea		1	1		1			1	D
Ampharete baltica	1	1		1	1	1			*
Ampharete cirrata			1			1			*
Aphelochaeta marioni		1							*
Arenicola marina	1				1				*
Aricidea minuta	1	1							*
Aricidea suecica					1				*
Bylgides sarsi	1		1	1	1	1	1		*
Capitella capitata				1	1				*
Dipolydora quadrilobata			1	1	1	1			*
Erinaceusyllis erinaceus	1								D
Eteone longa		1							*
Eumida sanguinea	1								*
Exogone naidina	1								D
Fabricia stellaris							1		D
Fabriciola baltica	1						1		G
Harmothoe imbricata	1								D
Harmothoe impar	1								*
Hediste diversicolor					1		1	1	*
Heteromastus filiformis	1	1	1		1	1			*
Lagis koreni	1	1	1	1					*
Levinsenia gracilis			1						*
Marenzelleria neglecta								1	ne
Mediomastus fragilis				1					D
Neoamphitrite figulus	1								*
Nephtys caeca	1	1		1					*
Nephtys ciliata	1	1	1	1		1			*
Nephtys hombergii			1	1		1			*
Nereimyra punctata	1								G
Nicolea zostericola	1								*
Paradoneis eliasoni	1	1	1						*
Parexogone hebes	1								D
Pherusa plumosa	1								D
Platynereis dumerilii	1								G
Polydora ciliata	1								*
Polydora cornuta	1	1			1		1		*
Pseudopolydora pulchra	1								*

Taxa	N3	N1	M2	OM18	K8	K4	K3	OM160	RL
Pygospio elegans		1		1	1		1	1	*
Scalibregma inflatum	1			1					G
Scolelepis foliosa					1				*
Scoloplos armiger	1	1		1	1	1	1		*
Sphaerodoridium balticum							1		D
Spio goniocephala					1				*
Terebellides stroemii	1		1			1			*
Travisia forbesii					1		1		G
Trochochaeta multisetosa				1					D
Porifera									
Chalinula limbata		1							D
Haliclona oculata	1								D
Leucosolenia sp.	1								ne
Priapulida									
Halicryptus spinulosus		1					1		ne
Pycnogonida									
Callipallene brevirostris	1								R
Pycnogonum litorale		1							D
species number 138	86	42	22	33	45	16	25	23	
abundance (ind m^{-2})	2285	659	433	1609	1427	331	5007	6775	
biomass (afdw g m^{-2})	13,1	22,8	25,2	1,8	6,8	1,9	4,8	7,6	

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CONTENT

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