Article

Major Baltic Inflows come in different flavours

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Ulrike Löptien [1,2] ✉, Matthias Renz[1] & Heiner Dietze[1,2,3]

The Baltic Sea is a marginal sea in northern Europe. Anthropogenic eutrophication and related deoxygenation are among its pressing environmental problems. To this end intermittent major salt water inflows from the North Sea are of major importance because they replace deep low-oxygenated waters with oxygenated surface water that sinks to depth after passing the shallow Danish Straits. Here we show, guided by machine-learning and backed by geophysical fluid dynamic modelling, that major inflows come in two "flavours" as a result of distinctly-different successions of the driving synoptic atmospheric patterns: (1) Relatively salty inflows, carrying mainly waters of pristine Atlantic origin, preconditioned by moderate high-pressure systems over the Baltic that are ultimately driven by gale force westerly winds. (2) Relatively sweet (fresh) inflows, preconditioned by pronounced high-pressure systems that build up oceanic barotropic pressure gradients across the Danish Straits. The latter, in conjunction with moderate to strong westerly winds, ultimately drive inflows that carry a mix of previously-exported brackish Baltic Sea water and salty Kattegat water - rather than more pristine Atlantic flavours. Our conceptual framework provides, for the first time, an explanation for the question why inflow strength is not directly linked to re-oxygenation of the deep Baltic.

The Baltic Sea is the largest body of brackish water in Europe covering 395.000 km² at an average depth of 55m. Close to a 100 million people distributed over 14 countries live in its drainage basin[1]. Their environmental footprint has been so worrisome that the intergovernmental Helsinki Commission (HELCOM) has been mobilised to protect the marine environment for almost half a century, already. Unfortunately and despite substantial efforts, such as drastic-reductions of nutrient loads, the Baltic Sea is still infamous for its hypoxic area which ranks among the largest anthropogenically-induced areas world-wide[2]. Among the respective triggers are eutrophication[2–8], rising temperatures[2,9–12] and increased stratification of the water-column[13–16]. Disconcertingly, there is evidence that the oxygen concentrations in the Baltic Sea may decrease even further in a warming world[17,18], which endangers fish stocks and higher life in general[19,20].

The Baltic Sea is characterised by a unique hydrographic structure, where seasonal convection is inhibited by the presence of a permanent halocline. This halocline acts as a barrier, separating the relatively fresh surface waters, which are strongly influenced by river runoff, from the more saline deep waters. The inflow of dense, salty, well oxygenated waters from the North Sea through the Danish Straits (Fig. 1) is the only mechanism to ventilate the deep waters below the halocline with dissolved oxygen[21] such that an effective oxygenation of the deep central Baltic Sea requires strong inflows over the entire water depth (barotropic) at Darss Sill (the entrance to

the Arkona Basin)[22]. Our study sets out to add to an extensive research history on these strong barotropic inflows, also dubbed Major Baltic Inflows (MBIs). We use a combination of machine learning and prognostic ocean circulation modelling. It builds on the recent disruptive increase in the accessibility of machine learning, computational power and data availability.

MBIs typically last for several days to weeks and occur mainly in winter or early spring[23]. They play a pivotal role since they balance de-oxygenation in the Baltic by replacing deep de-oxygenated waters with salty oxygenated surface water from the North Sea entering the Baltic via the shallow Danish Straits whereafter it cascades at the bottom from basin to basin (Arkona, Bornholm, Gotland) ever further into the Baltic. To this end, MBIs exert control on the overall biogeochemical turnover because depleted oxygen concentrations set the scene for denitrification (as opposed to aerobic remineralisation of organic matter) and the release of dissolved inorganic phosphorous from the sediments to the water column. In recognition of their vital role in shaping the marine environment, MBIs have been studied extensively[21,24–35]. In terms of atmospheric drivers of MBIs, early studies[24,26,28] have already pointed out, that a preconditioning period with easterly winds is typically followed by a period of strong westerly winds. Based on statistical analysis, a subsequent study[29] refined the picture by presenting evidence that high river runoff in the Baltic has the potential to rebut major inflows. Numerous follow-up studies added to the discussion on the relation

[1]Department of Computer Science, University of Kiel (CAU), Christian-Albrechts-Platz 4, 24118 Kiel, Germany. [2]Institute of Geosciences, University of Kiel (CAU), Ludewig-Meynstr.10, 24118 Kiel, Germany. [3]Department of Chemistry, King's College London, London, UK. ✉e-mail: ulrike.loeptien@ifg.uni-kiel.de

Fig. 1 | Overview map. Baltic Sea bathymetry. Depths[73] in metres. The inlay shows the Danish Straits, through which the North Sea waters are imported into the Baltic.
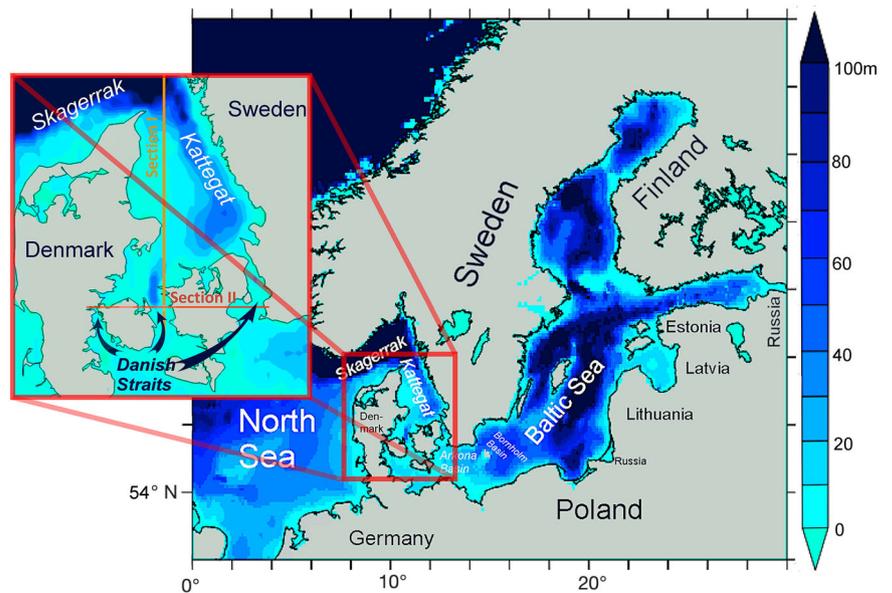
between atmospheric drivers and MBIs[29,36–40] or extreme sea levels in the Baltic[41]. In our view, a relatively recent study[37] is especially intriguing in that they relate MBIs to specific cyclone paths and, further, distinguish between large volume exchanges (across the Danish Straits) and MBIs, arguing that the latter is controlled also by salinity and stratification of the deep basins of the Baltic (in contrast to the large volume exchanges which do not necessarily import oxygenated salty surface water that sinks to depth in the Baltic).

Despite decade-long incremental progress, the understanding of drivers of MBIs is still incomprehensive such that forecasts based on meteorological patterns are generally not satisfactory[42]. Among the reasons is that it is not evident what distinguishes a MBI from those large volume exchange events (between North Sea and Baltic Sea) that fail to ventilate the deep Baltic. Here we add to the ongoing effort to disentangle the atmospheric drivers of MBIs by exploiting the combination of a relatively recently published time series of barotropic Baltic inflows[23] and the fifth generation ECMWF atmospheric reanalysis[43,44] (ERA5) with contemporary data mining techniques (clustering) in order to isolate the atmospheric triggers of MBIs. We focus on the link between MBIs and atmospheric patterns directly over the Baltic. In a second step, we test our statistically-inferred cause-and-effect relationships in a numerical geophysical fluid dynamic model of the Baltic Sea (MOMBA[45–47]) that is based on first principles (such as Newton's Law). This confirms the atmospheric drivers and reveals the existence of two conceptionally-different inflow types.

Results

Favourable atmospheric conditions

Our study is based on the barotropic inflow time series compiled by Volker Mohrholz (Institute for Baltic Sea Research Warnemünde)[23]. It is derived from long-term observations of sea level, river discharge, and salinity from the Belt Sea and the Danish Sounds. We define MBIs as inflows that last longer than 5 days (after starting at the Belts; in contrast to starting at the Sound[23]) and supply more than 1 Gt salt to the Baltic (please refer to the Method Sect. for a discussion of the MBIs definition; a visualisation is provided in Fig. 1 of the Supplement). We link the time series of MBIs with atmospheric sea level pressure fields from 20 days prior to MBIs until 10 days thereafter using unsupervised learning (k-means clustering method[48,49] with Euclidean distances, calculated in the space/time domain, in combination with dynamic time warping[50,51]; details are provided in the Method Sect.). We consider the time period from 1991 onwards, opting for a compromise between a sufficient amount of data and a well-developed observational network[23,52] ensuring data quality. Our approach identifies 2

clearly distinct clusters with 19 and 6 members, respectively. We use the *Silhouette Score*[53] to assess how well each cluster member fits within its cluster (essentially by putting respective cohesion into relation to separation) and obtain a score of 0.56 indicating that the clustering is meaningful (cf. supplementary Figs. 2 and 3). Note that some inflows feature characteristics of both clusters, such as the 1993 event.

Our cluster analysis confirms foregoing studies in that it links all major inflows to a pre-conditioning phase with an atmospheric high-pressure system over the central Baltic followed by the actual inflow phase characterised by pronounced westerlies related to a low-pressure system up North (i.e. north of 60°N; Fig. 2 shows the result of the clustering while supplementary Fig. 4 illustrates the corresponding absolute sea level pressure and wind fields). Further, it expands on previous knowledge in that it identifies two distinctly-different clusters where, respectively, either the high-pressure during preconditioning or the low pressure during the inflow phase is more pronounced. More specifically we find:

(1) Cluster CLASSIC, representing the "classical" or canonical picture of a major inflow starting off with a pronounced high-pressure system over Scandinavia and the north-western part of the Baltic Sea during a 14- to 20-day-long preconditioning phase. During the 5 days prior to an inflow the intensity of this high-pressure system is consistently relatively pronounced and the agreement between the cluster members is high (see supplementary Fig. 5). The inflow starts with a weakening of the high pressure when the major wind direction starts shifting to westerly winds. During the transition to westerlies the agreement between the cluster members is relatively low with some members featuring winds of only moderate strength. Variations of CLASSIC include local disturbances, that refer to short-term unstable weather conditions during the preconditioning phase and variations in the position of the core of the high-pressure system. The majority of 19 out of 25 events refers to this cluster and the duration ranges from 6 to 21 days (see Fig. 2b).

(2) Cluster STORMY, characterised by near-gale force westerly winds over the southern part of the North Sea, the Kattegat and the Baltic Sea during the inflows. The preconditioning with high-pressure system over the central Baltic and associated easterly winds is much weaker than in CLASSIC (Fig. 2 and supplementary Fig. 4). The duration of STORMY events ranges from 6 to 11 days.

Flavours of inflows

Unsupervised learning statistically linked MBIs to the two distinctly-different successions of synoptic atmospheric patterns, dubbed CLASSIC and STORMY. These patterns are fed into in a Geophysical Fluid Dynamic
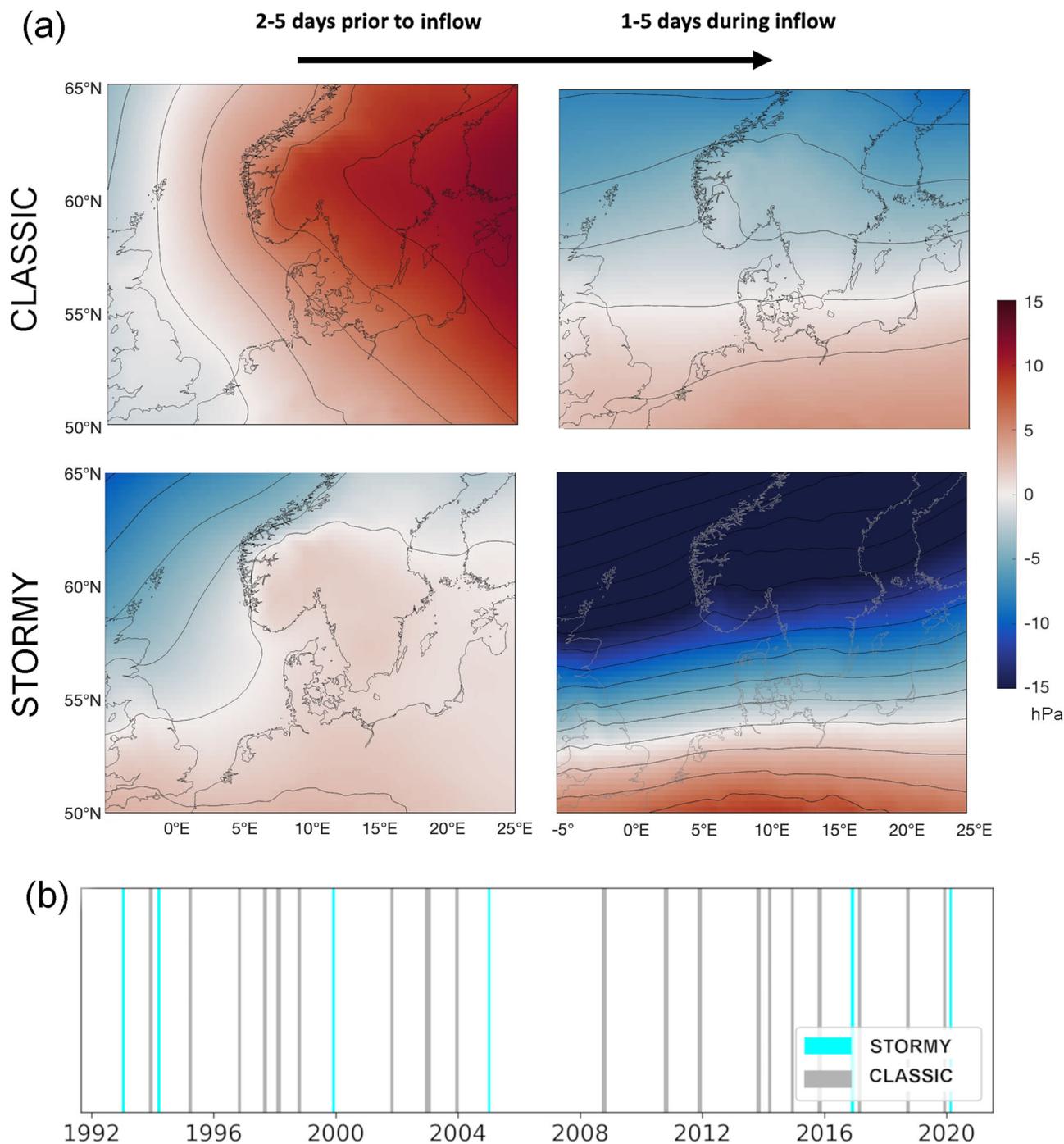
Fig. 2 | Sea level pressure anomalies referring to the cluster centres. a Mean sea level pressure anomalies before (left panels) and during a major inflow (right panels) representative for the centres of cluster CLASSIC (upper row) and STORMY (lower row). Respective averaging periods (2 to 5 days prior, and 1 to 5 days during inflow) emphasise the conceptual differences. **b** Timing and duration of CLASSIC (grey bars) and STORMY (cyan bars) events.

model of the Baltic Sea which simulates the ocean circulation by adhering to first principles (i.e. solving an approximation of the Navier–Stokes equations) in order to: (1) confirm that there are actual causal links to MBIs and (2) elucidate respective inflow characteristics.

Feeding the cluster midpoints of CLASSIC and STORMY into the geophysical fluid dynamic model yield—indeed—MBIs. They total at a volume (salt) import to the Baltic of 111 km³ (1.8 GT) and 182 km³ (3.7 GT), respectively. This is well in the range of typical MBIs thereby confirming our statistical links with first-principles modelling. In terms of inflow characteristics we find differing flavours: peak salinities in the inflowing waters are ≈25% more salty for STORMY compared to CLASSIC. The underlying

mechanisms are that CLASSIC MBIs start off with a substantial export of water out of the Baltic Sea (driven by an atmospheric high-pressure system over the central Baltic, related to easterly winds) during the preconditioning phase. This water overlays on top of the saltier Kattegat waters, and is reimported (along with saltier waters of more pristine Atlantic characteristics) once the winds shift westward during the actual inflow phase. This reimport reduces the average salinity of the inflowing water. In contrast, STORMY MBIs are characterised by a weaker high-pressure system during the preconditioning phase such that they feature less export of relatively fresh water out of the Baltic during preconditioning. This results in saltier inflows also because there is less fresh water (of Baltic origin) in Kattegat at the surface and the intense westerly
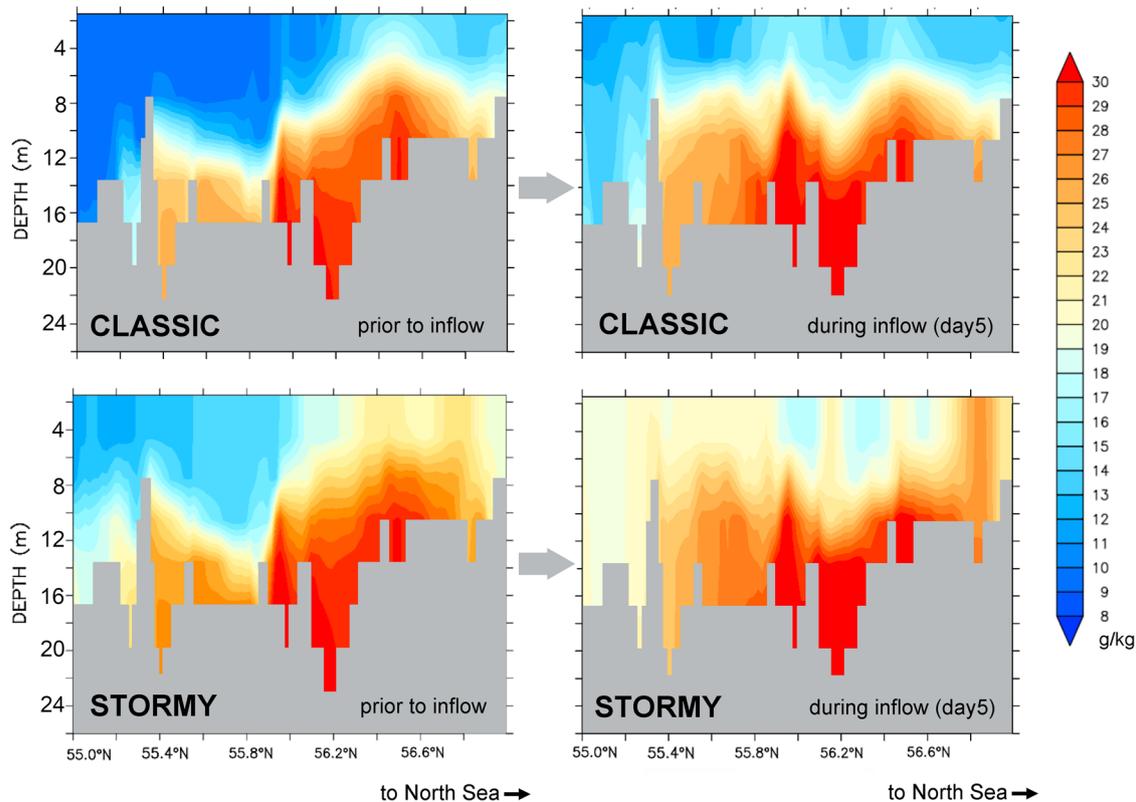
Fig. 3 | Kattegat salinity conditions. Meridional salinity section through the Kattegat at 11°E at the onset of the inflow (left) and at day 5 during the inflow (right). The upper row refers to CLASSIC and the lower row to STORMY events. The respective section is marked in Fig. 1.

winds can mix deeper and saltier Kattegat waters up to the surface where they are transported into the Baltic (Figs. 3, 4). In CLASSIC the latter process is suppressed by the stratifying effect of the fresh water of Baltic origin and the generally weaker westerly winds. An illustration of the characteristics of CLASSIC and STORMY is provided in Fig. 5.

A set of sensitivity experiments (as outlined in detail in the Method Section and listed in Table 1) reveals that these results, with CLASSIC being rather sweetly flavoured (fresh) and STORMY rather salty, are robust towards changes in the initial conditions (20 days prior to inflow) (see also Fig. 4). Further respective details are: for CLASSIC we find the volume transport is more robust towards changes in the initial conditions (less than 15% deviation from the reference value in our experiments) than the salt transport (less than 22% deviation from the reference value) and for STORMY both, volume and salt deviations from the reference values, are at a maximum of ≈10% in our sensitivity experiments. We conclude that the salinity of CLASSIC MBIs are more affected by the internal state of the Baltic Sea than is the case for STORMY. This suggests that their flavour is more prone to change in response to anticipated future climate changes that affect the salinity[54] and stratification[55] of the Baltic Sea and the Kattegat.

As concerns the impact of anticipated atmospheric circulation changes such as (1) an amplification of extreme cyclones[56,57] and (2) a slowdown of the translation of synoptic patterns[58] a set of sensitivity experiments (cf. Methods) yields: a 20% increase in the strength of atmospheric pattern increases the salt input to the Baltic by 17% for CLASSIC and 11% for STORMY, while the volume increases around 13% for both types of inflows (in absolute numbers: 14 km³ (0.3GT salt) and 23 km³ (0.4GT salt) for CLASSIC and STORMY, respectively). In contrast, the responses to changes in the duration of the inflow phase are similar for CLASSIC and STORMY: A slowdown of cyclone speed mimicked by doubling the length of the inflow phase (by "stretching out" respective atmospheric conditions in time) drives increases of 27 km³ (0.5GT salt) and 44 km³ (1GT salt) for CLASSIC and STORMY, respectively (referring to a ≈ 25% increase for volume and salt irrespective of the type of inflow). Thus, doubling the length of the inflow

phase has a relatively large impact on the total amount of salt and volume transport for both types of inflows. In contrast, the impact of a 20% increase in the strength of atmospheric pattern is weaker and can, especially for CLASSIC, be comparable to a change in the initial state of the Baltic.

Discussion

We investigated the link between atmospheric drivers and MBIs. Employment of Machine Learning identified two distinct atmospheric pattern that create distinctly different flavours (characteristics) of inflows when applied to a geophysical fluid dynamic model. We anticipate that similar techniques and findings will apply to many of those coastal or marginal seas world-wide that are flushed by waters of distinctly differing origins (e.g. the Arctic Ocean, the vicinity of the Amazonas river plume[59] or coastal urban water systems[60]). This is of relevance because anthropogenic climate change is not restricted to warming but may well impinge on the temporal evolution of synoptic atmospheric patterns locally. One such example are atmospheric blocking events, that are typically linked to the formation of CLASSIC events during the preconditioning phase. These events are characterised by persistent, quasi-stationary high-pressure systems that disrupt the typical westerly flow of the jet stream[61]. Even though projections of atmospheric blocking events in a warming climate are still associated with considerable uncertainties[62,63], it appears timely to develop the tools to investigate regional and very detailed links between the temporal evolution of synoptic patterns and oceanic environments. As for the Baltic Sea, for example, past studies have been puzzled that the inflowing amount of salt is not necessarily proportional to the oxygen supply of the deep waters[21,22]. This disparity, although very local in nature, maps onto a misfit between MBI strength and their oxygenating effect on the Baltic Sea and ultimately on the uncertainty of its ecological health in a warming world.

Our results show that inflows come in two flavours depending on the driving temporal evolution of atmospheric synoptics: either the inflowing water is relatively salty or fresh which directly affects its capability to oxygenate the deep Baltic Sea. Salty inflows, driven by near-gale force westerly
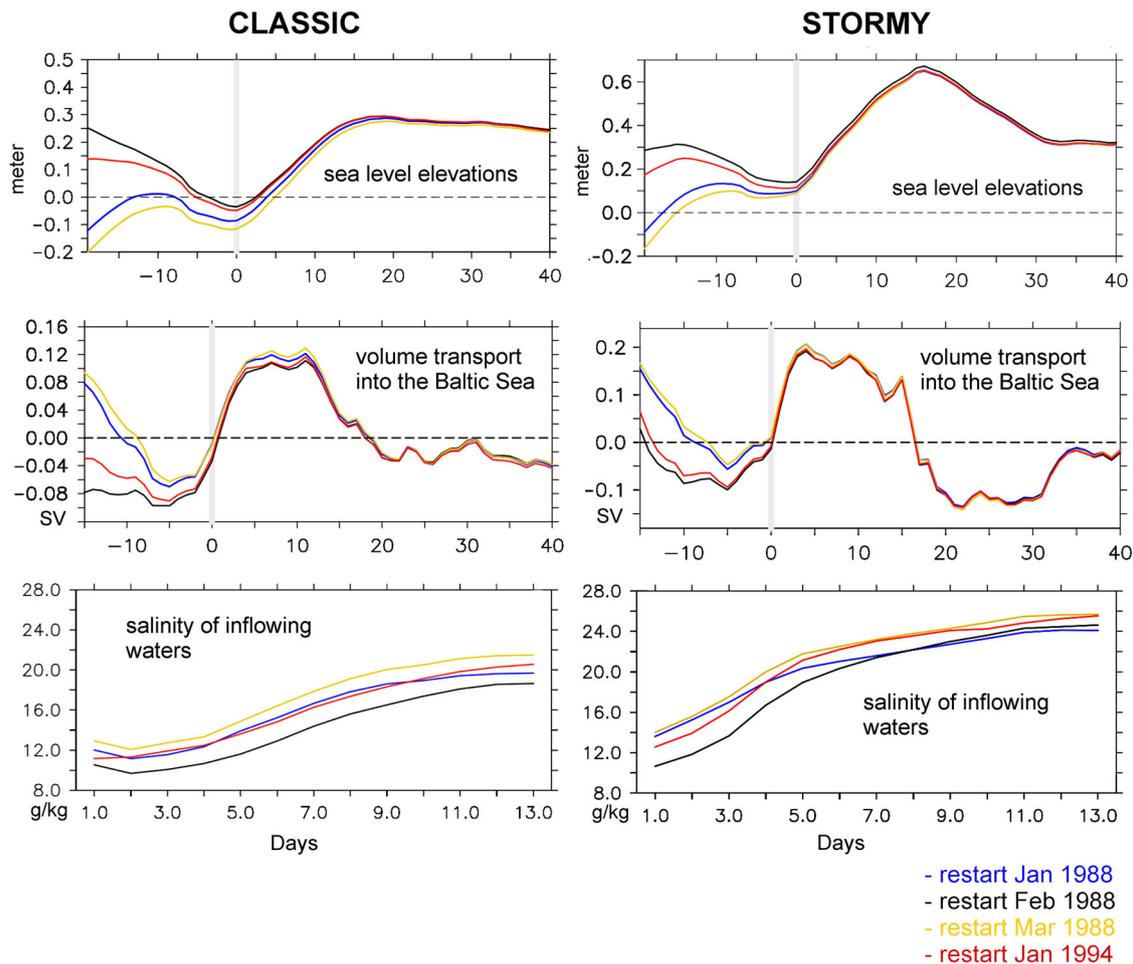
Fig. 4 | Sensitivity experiments. Simulated inflow dynamics for idealised wind and sea level pressure forcing representative for the clusters CLASSIC (left column) and STORMY (right column). The upper row shows simulated sea level elevations, averaged for the entire Baltic Sea. The middle row shows integrated transport through the Danish Straits at the zonal section along 55.5°N marked in Fig. 1. The lower row shows the mean salinity of the inflowing waters during the inflows. Note that y-axis ranges differ between panels.

winds over the southern part of the North Sea, Kattegat and the Baltic Sea during the inflows, consist of waters of more pristine Atlantic origins. They are denser throughout the whole inflow period and a larger fraction of this inflowing water has the potential to be dense enough to sink to the deepest layers after entering the central Baltic, while fresher water interleaves at shallower depths corresponding to respective neutral buoyancies[64]. Hence, salty inflows are typically more effective in replacing deep hypoxic or sub-oxic waters (i.e. waters that suffer from oxygen deficiency < 2 mL L^{-1} [12]) than fresher inflows. As a side note: saline inflows increase the stratification of the Baltic which may introduce an antagonistic effect by excluding subsequent deep penetration of fresher inflows[65,66] and by limiting the ventilation from above[35]. Fresher inflows, on the other hand, are characterised by a pronounced high-pressure system over Scandinavia and the north-western part of the Baltic Sea during a 14 to 20-day-long preconditioning phase and carry more of "re-imported" Baltic Waters which subsume further up in the water column after entering the Baltic. Hence, the fraction of dense inflow water that reaches the deep levels of the central Baltic is generally much lower for this type of (relatively fresh) inflows. Also, the re-import of waters of Baltic origin renders the respective state of the Baltic at the onset of a respective MBI more impactful for this type. In this context, Fig. 4 explains why anomalous river runoff can have a relatively large twofold effect on CLASSIC MBIs[29]: For one, anomalous high river runoff reduces the salinity of the Baltic Sea[67]. Second, river runoff alters the sea level of the Baltic (on seasonal and inter-annual timescales in the order of centimeters to decimetres[68]). An anomalous high sea level at the onset of a

CLASSIC MBI maps onto more outflowing (fresh) waters from the Baltic Sea during the preconditioning phase which then is re-imported during the actual inflow phase. This freshening effect on MBIs is less effective during STORMY events because they re-import less water of Baltic Sea origin.

In terms of robustness of our results we report, backed by a suite of geophysical fluid dynamic model simulations, that the differences between CLASSIC and STORMY are relatively insensitive towards translation speed of atmospheric synoptics (Tab. 1). A prominent confirmation of our results is the historic and enigmatic 2014/2015 MBI: although high in volume and anomalously long in duration (≈ three weeks) its effect on the oxygenation state of the Baltic was so underwhelming that reports suggested potential reasons and concluded that "... *the strength of a major inflow event alone cannot be used to predict the oxygenation impact* ..."[22]. This is in line with our results that classified the 2014/2015 MBI as CLASSIC, i.e. consisting of relatively fresh, re-imported water that had left the Baltic during a pre-conditioning phase characterised by a strong outflow of fresh Baltic waters.

Caveats remain, the most significant being that despite the MBI time series being derived from one of the longest tide-gauge records globally, the number of independent observations is still relatively low. This limitation impacts the accuracy of our machine learning results. However, since the statistical links identified by the machine learning model were corroborated through first-principles modelling (using a numerical geophysical fluid dynamics model), we consider the findings to be robust.

In summary, we find that the composition of water in the Kattegat is exerting major control on the effectivity of MBIs in oxygenating the Baltic.

Fig. 5 | Characteristics of CLASSIC and STORMY.
Sketch of the main characteristics of CLASSIC and
STORMY events before (left column) and during an
inflow (right column). The thin grey line close to the
sea surface refers to the "normal" mean sea level of
the Baltic. The depicted low pressure systems during
the inflow phase refer to rather moderate and near
gale force winds for type CLASSIC and STORMY,
respectively. Relatively dark colours in the ocean
represent denser waters at depth, whereas blue
indicates brackish and dark red indicates salty
waters.
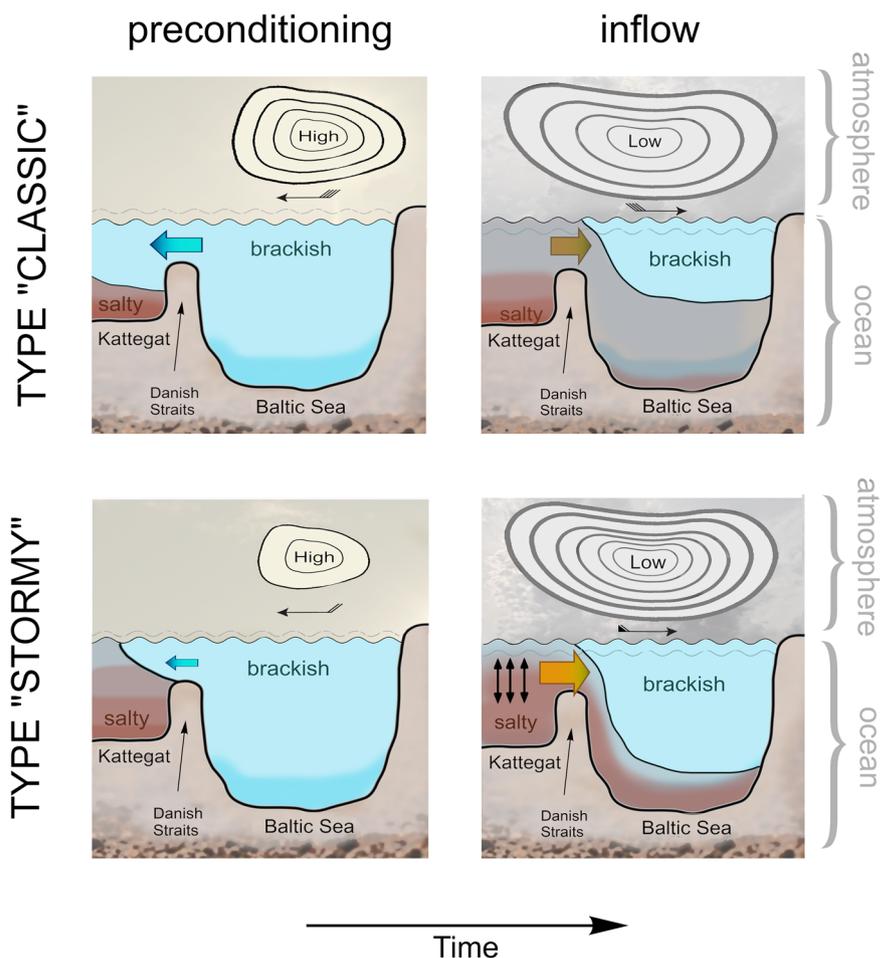
Table 1 | Transports into the Baltic Sea during inflows

Experiment description	Volume-Transports (CLASSIC/STORMY)	Salt-Transports (CLASSIC/STORMY)
Reference simulations	111 km³/182 km³	1.8 GT/3.7 GT
Change of initial conditions	95–115km³/169–182km³	1.4–2.1/3.4–3.9 GT
+ 20% amplified atmospheric pattern	125km³/205km³	2.1 GT/4.1GT
+ 100% stretched inflow phase	138 km³/226 km³	2.3 GT/4.7 GT

Sensitivity experiments that apply the mean atmospheric winds and sea level pressure forcing representative for CLASSIC and STORMY to the Baltic Sea geophysical fluid dynamic model MOMBA.
Respective transports into the Baltic Sea, integrated over respective events, are through the Danish Straits across 55.5°N.

Hence, we conclude that forecasts of the evolution of Baltic Sea oxygenation in a warming world must be based on a comprehensive understanding of mixing processes in the Kattegat, as traced, for example, by Rasmussen (1995)[69].

Methods
Identification of Major Baltic Inflows
Our study is based on the time series kindly provided by the Institute for Baltic Sea Research Warnemünde (IOW)[23]. This time-series of barotropic Baltic Inflows and their mean properties were derived from long-term observations of sea level, river discharge, and salinity from the Belt Sea and the Danish sounds. For the presented study we had to define which of the inflows we regard as "major". The problem being here that different criteria exist in the literature where it has been stated that " ... *The size class distribution of barotropic inflow events depicts a nearly exponential shape ...*" and that" ... *there is no local minimum in the distribution that provides a proper reasoning for the separation between MBIs and minor barotropic events ...*". Hence, the classification as "major" remains " ... *in some way artificial ...*" and it varies from study to study which events are considered as

major[23]. According to the original criteria from the 1990s, MBIs are characterised by a high bottom salinity at Darss Sill (at the entrance to the Arkona Basin) and a weak stratification, lasting for at least five consecutive days[24]. This criterium is not directly applicable because the time series considered in this study[23] does not include information on bottom salinity and stratification (because these could not be consistently reconstructed). Here, we use the original 5 day criterion (onset defined as start of inflow at the Belt Sea as provided in the respective time series) with an additional constraint based on salt transport (MBI must supply more than 1 Gt). The rationale being that smaller and baroclinic inflows generally fail to supply much salt to the Baltic. Both criteria are illustrated in the Supplement (supplementary Fig. 1). We identified 25 inflow events during the period 1990-2022.

Identification of favourable atmospheric conditions and clustering
For the cluster analysis we use atmospheric sea level pressure fields from 20 days prior the identified events until 10 days after the events. 12-hourly

sea level pressure fields were obtained from the ERA5-reanalysis project[43,44]. These data are provided on a latitude-longitude grid of 0.25 degrees. We consider the time period from 1991 onwards, opting for a compromise between the total amount of available data and high data quality based on modern comprehensive observational networks[52]. Also, there were not many accurate observations available during the period 1976-1991 to reconstruct the inflows[23]. Our focus is on the atmospheric conditions in the Baltic Sea region, ranging from 5˚W to 25˚E and 50˚N to 65˚N. Prior to the clustering the temporal-spatial means were removed from the time series.

We employ the k-means clustering method[48,49]. K-means clustering is one of the most popular unsupervised learning algorithm used in machine learning. It is an iterative algorithm that contains a stochastic element by randomly initialising the clusters. Our study refers to the solution with the best separated clusters after repeating the algorithm 10 times, while testing to identify a total number of up to 14 clusters. While some minor changes in the attribution to the clusters occurred when repeatedly running the algorithm, our main findings remain robust.

To determine the distances between the temporal evolutions of sea level pressure anomalies we use Euclidean distances, calculated in the space/time domain. The k-means algorithm requires the number of clusters to be specified. We apply the Silhouette Score criterion, which measures the similarity of objects to their own and other clusters, and determine the optimal numbers of clusters by opting for a particularly large value[53]. Silhouette Scores range from -1 to $+1$, where a high value indicates that the object is well matched to its own cluster and poorly matched to neighbouring clusters. In real world application, a score of one is typically never reached and 0.7 is already considered as indicative of "strong" clustering.

Our first "naive" attempt did not yield satisfactory results as Silhouette Scores were low and increased with the number of clusters without revealing clear separations between the clusters. A more sophisticated approach, including dynamic time warping[50,51] which measures the similarity between two temporal sequences that may vary in speed, brought success: We "warped" the sequences of sea level pressure anomalies in the time dimension to determine a measure of their similarity independent of certain non-linear variations in the time dimension. We apply the time warp uniformly to all spatial points and the time shift was determined by minimising the distance between the time evolutions of the sea level pressure fields. This approach finds similarities in synoptic systems even if they differ in their translation speed - as long as they are similar in strength and travel similar paths in a similar sequence with other synoptic systems. We allowed for a maximum warping in time of 1.5 days.

Using dynamic time warping, we identified 2 clearly distinct clusters, as indicated by a relatively high Silhouette Scores of 0.56 (see supplementary Figs. 2 and 3). Cluster centres are calculated by averaging the respective cluster members that were time-warped relative to the median cluster member and interpolate the time warped sea level pressure evolutions on the original time axis. Since the time warping is repeatedly applied to 2 time evolutions each, this procedure might introduce a certain smoothing effect on the respective sea level pressure anomalies which is, however, kept in check by limiting the maximum time shift to 1.5 days.

Model simulations and forcing
After identifying the clusters, we use the sea level pressure and wind fields that refer to the cluster centres to force MOMBA, a geophysical fluid dynamic model of the Baltic Sea based on first principles. The aim of the model simulations is to reassure the (statistical) results of the clustering. Additionally, we aim to explore whether systematic differences exist between the identified types of MBIs. The respective forcing fields were obtained by following the identical averaging procedure as for the cluster centres without subtracting the mean beforehand (cf. Supplementary Fig. 4). Additionally, sea level elevations in the North Sea are prescribed in our model and were determined statistically via the so called Baltic Sea-index (BSI), which measures the atmospheric sea level pressure difference between Oslo in Norway and Szczecin in Poland[70]. The remaining atmospheric boundary conditions refer to the original ERA5-reanalysis data[43,44].

The ocean model MOMBA is an eddy-rich configuration of a Baltic Sea coupled ocean-circulation-ice model. The MOMBA model[45] received an update such that it captures deep water dynamics more realistically. The changes are outlined in the Supplements in Sect. 2 (supplementary Figs. 6 to 10 provide an evaluation of the updated model). The model run time covers 2 months starting 1. February 1988 for the two reference simulations, referring to CLASSIC and STORMY. We chose February1988 because salinity has been relatively low and it was a year without major inflows.

A suite of additional sensitivity experiments explores the impact of the initial state of the ocean and the reaction of the model to intensity and frequency changes of the atmospheric pattern (Table1). Specifically, we use January 1st, 1988, March 1st, 1988 and January 1st, 1994 as alternative initial conditions while keeping the atmospheric forcing unchanged. Note that, in contrast to the relatively low salinity in the Bornholm Basin in 1988, the salinity was relatively high in 1994. Thus, our sensitivity simulations are designed to provide some envelope of typical past states of the Baltic. Even so, we cannot rule out that more extreme cases might also have occurred in the past.

Two sets of sensitivity experiments are motivated by anticipated future changes that refer to (1) an amplification of synoptic systems[56,57] and (2) to a slowdown of the translation of synoptic systems[58]. We tested a 20% increase in the strength of the atmospheric pattern and a doubling the length of the inflow phase relative to the reference simulations. All experiments share the same prescribed salinity and temperature for the North Sea. From the model simulation we analyse the mean sea level elevations for the Baltic Sea, transports through the Danish Straits which were integrated at 55.5˚N as well as the pre-conditions in the Kattegat region.

Data availability

Code availability

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Correspondence and requests for materials should be addressed to Ulrike Löptien.

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