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Characteristics and Chronology of Baltic Inflows in October and December 2023 According to NEMO Reanalysis — Virtual Cruise

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Abstract

Barotropic saline Baltic inflows (SBIs) occurred in the period of 01.09.2023–20.02.2024 are analyzed using the NEMO reanalysis data. To test the model product, it is shown that it adequately reproduces the observed time series of salinity and temperature on depth and time of 32 yr long (1993–2024) at a monitoring station BY15 located in the Gotland Deep. The water volume imported to the Baltic Sea with the SBIs being estimated from the *in situ* observations of the sea level and salinity is found to be highly correlated with the direct estimates based on the NEMO reanalysis data. Comparison of the October and December 2023 SBIs reveals that quantitative characteristics of an SBI, such as the imported water volume and salt mass, being important nevertheless do not fully determine the subsequent evolution of the salinity field in the remote basins of the Baltic Sea. Apart from the imported water volume and salt mass the synoptic variability of the wind field is of paramount importance. Keeping in mind that the salt water transport in the bottom layer of the Bornholm Channel, Słupsk Furrow, and Hoburg Channel towards the deepest Baltic basins is most intense at northwesterly, northerly, and northwesterly winds, respectively, one may expect that a long-lasting northwesterly wind period immediately following the inflow event is the most favorable for ventilation of the Baltic Sea deep layer.

Keywords: Major Baltic Inflows, barotropic saline Baltic inflows, Danish straits, Darss Sill, Drogden Sill, water volume transport, salt mass transport, wind forcing, compensatory baroclinic current in the bottom layer, NEMO reanalysis

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Характеристики и хронология балтийских заток в октябре и декабре 2023 г. по данным реанализа NEMO — виртуальный рейс

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Аннотация

Баротропные затoki соленой североморской воды в Балтийское море (SBIs), произошедшие в период с 01.09.2023 по 20.02.2024, анализируются с использованием данных реанализа NEMO. Тестирование модельного продукта показало, что он адекватно воспроизводит наблюдаемые временные ряды солености и температуры в зависимости от глубины и времени продолжительностью 32 года (1993–2024 гг.) на станции мониторинга BY15, расположенной в Готландской впадине. Объем воды, поступающей в Балтийское море посредством SBIs, оцениваемый на основе наблюдений уровня моря и солености, оказался в высокой степени коррелирующим с прямыми оценками, основанными на данных реанализа NEMO. Сопоставительный анализ SBIs, произошедших в октябре и декабре 2023 года показывает, что их количе-

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ственные характеристики, такие как объем приносимой воды и массы соли, хотя и важны, тем не менее, не в полной мере определяют последующую динамику поля солёности в отдалённых бассейнах Балтийского моря. Помимо приносимого объема воды и массы соли важнейшее значение имеет синоптическая изменчивость поля ветра. Учитывая, что перенос соленой воды в придонном слое Борнхольмского канала, Слупского желоба и Хобургского канала в направлении наиболее глубоких впадин Балтийского моря наиболее интенсивен при северо-западном, северном и северо-западном ветрах соответственно, можно ожидать, что продолжительный период северо-западного ветра, который сразу следует за затопом в Датские проливы и Арконский бассейн, является наиболее благоприятным для вентиляции глубинного слоя Балтийского моря.

Ключевые слова: главные балтийские затоки, баротропные затоки соленой североморской воды в Балтийское море, Датские проливы, порог Дарс, порог Дрогден, перенос объема воды, перенос массы соли, ветровое воздействие, компенсационное бароклинное течение в придонном слое, реанализ NEMO

1. Introduction

Water and salt exchange between the Baltic Sea (BS) and the North Sea occurs through the Great and Little Belt straits and the Sound (Øresund) Strait (see Fig. 1). Salt water from the North Sea enters the Baltic Sea through the straits, mixes with fresh river runoff and precipitation, and a less salty mixture of the same volume, minus evaporation, flows back through the straits into the North Sea. The shallowest points on the routes of salty North Sea waters into the Baltic are the Darss (min. thalweg depth is 19 m) and Drogden (min. thalweg depth is 8 m) sills for the flows through the Belt straits and the Sound Strait, respectively. Both routes unite in the Arkona Basin (max. depth is 48 m) and then the common route goes northeast into the Bornholm Deep (max. depth is 105 m) via the Bornholm Channel (min. thalweg depth is 45 m). After the Bornholm Deep, the salt waters continue east into the Słupsk Furrow (max. depth is 90 m) via the Słupsk Sill (min. thalweg depth is 56 m). Then one branch turns northeast to the Gotland Deep (maximum depth is 227 m), and the second goes southeast to the Gdansk Deep (maximum depth is 105 m).

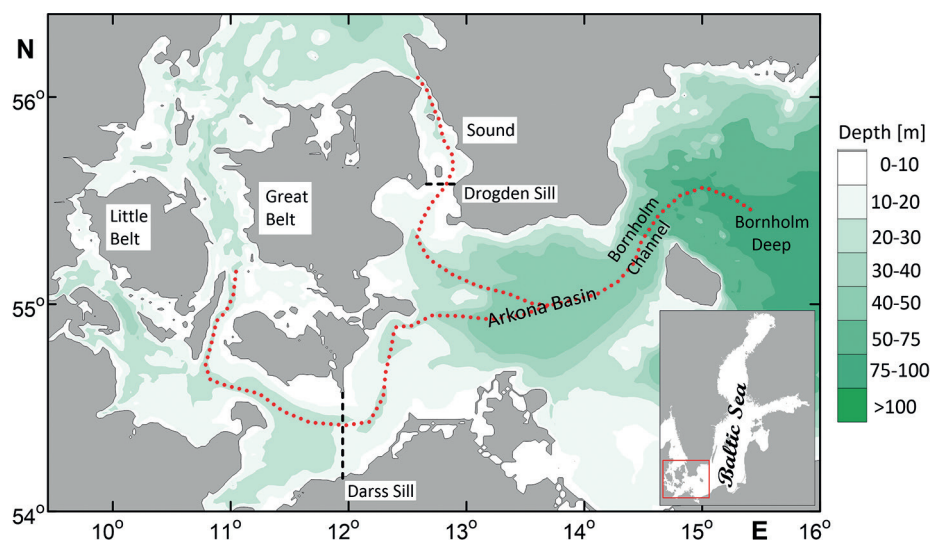


Fig. 1. Bathymetry map of a transition zone between the North and Baltic seas and the southwestern Baltic Sea. The black dotted lines represent the virtual zonal and meridional transects through which the water volume and salt mass imported to the Baltic Sea were calculated. The red dotted lines represent the virtual transects along the inflow route on which the water salinity was analysed

As a result of a limited water exchange with the North Sea and large river discharge, an estuarine type circulation is formed in the BS with a lower (deep) saline layer separated from the upper layer of low salinity by a powerful halocline/pycnocline. Hypoxia develops in the deep layer, and the only effective way of ventilation of the deep layer is the so-called Major Baltic Inflows (MBIs), when a huge volume of salty North Sea water of more than 200 km³ enters the Baltic Sea during a short period of several days. MBIs occur once every few years, there may be 10 years without an MBI. For an MBI to occur, a rare combination of circumstances is needed, when long-lasting easterly winds drive water out of the BS, greatly lowering the water level relative to the North Sea, and then a sudden westerly

hurricane wind rises, driving salt water through the straits into the Baltic Sea. MBIs usually occur in the second half of autumn — first half of winter and are barotropic in nature, when the entire water column at the Darss and Drogden sills has a vertically uniform high salinity (above 20 g/kg or so) across the depth and is transported unidirectional.

The MBIs are the largest of the Baltic Saline Barotropic Inflows (SBIs) that are usually occur several times a year [3, 4]. Mohrholz [4] developed an approach to estimate the volume of water and salt mass imported into the BS with SBIs based on historical time series of sea level and salinity since 1887. The volume transport $Q(t)$ was calculated through the change of the mean sea level in the BS multiplied by the sea surface area minus river runoff, precipitation and evaporation. Observations at the Landsort and Landsort Norra, published by SMHI Opendata server [5], were taken for the time series of the mean sea level of the BS. The sea level data at the Landsort were pre-filtered with 1.2 days cut off period to exclude the appearance of seiches, inertial motions, and local wind surges. The response period of the BS mean level to external barotropic forcing is 10 days [2]. This is used to determine whether consecutive inflow events refer to a single SBI.

To calculate salt water transports to the BS, the volume transport $Q(t)$ was split into the volume transports through Belt $Q_B(t)$ and Sound $Q_S(t)$ with a fixed ratio $Q_S(t)/Q_B(t) = 0.28$.

Normally, there is a salinity front between brackish BS water and the saline water of the Kattegat. During outflow event the front is located at the northern edge of the Danish Straits. To initiate an inflow of high saline water into the BS, the salinity front has to be moved beyond the Darss Sill in the Belt and the Drogden Sill in the Sound. This is a precursory period of an SBI [3], which lasts 5–25 days. The volume transports in the Belt and the Sound, $Q_B(t)$ and $Q_S(t)$, obtained from volume change of the BS, were used to estimate the approximate positions $p_B(t)$ and $p_S(t)$ of the salinity front for each channel. During inflow conditions the simulated salinity front was moving from the Kattegat ($p(t) = 0$) toward the Baltic until it reached the Baltic edge of the channel ($p(t) = 1$), and vice versa. If the same equations are used for both channels, then the equation for the Belt is given. The front positions were calculated stepwise for each time step t of Δt duration, using an effective buffer volume V_{buffer} of 110 km³ for the Belt and 10 km³ for the Sound, respectively:

$$p_B(t+1) = p_B(t) + \frac{Q_B(t) \cdot \Delta t}{V_{buffer}} \text{ with } \begin{cases} p_B(t+1) = 0 & \text{for } p_B(t+1) < 0, \\ p_B(t+1) = 1 & \text{for } p_B(t+1) > 1. \end{cases} \quad (1)$$

Time series of inflowing water volumes, $V_B(t)$ and $V_S(t)$, were calculated from the time series of barotropic transports, $Q_B(t)$ and $Q_S(t)$, as:

$$V_B(t) = Q_B(t) \cdot \Delta t \text{ with } \begin{cases} V_B(t) = 0 & \text{for } Q_B(t) < 0, \\ V_B(t) = V_B(t) & \text{for } Q_B(t) \geq 0. \end{cases} \quad (2)$$

The salt mass $S(t)$ imported into the BS was estimated by multiplying the inflowing water volume $V(t)$ by the mean salinity s . Only transports at times when the salinity front $p(t)$ is located at the Baltic side ($p(t) = 1$) were counted as import of saline water into the BS:

$$S_B(t) = V_B(t) \cdot \rho \cdot s_B(t) \text{ with } \begin{cases} S_B(t) = 0 & \text{for } p_B(t) < 1, \\ S_B(t) = S_B(t) & \text{for } p_B(t) = 1. \end{cases} \quad (3)$$

where ρ is the mean water density [ton/m³] for the Belt and the Sound. According to the methodology for identifying the SBIs [4], in 2023 the most voluminous saltwater inflows took place in October and December ranking 26th (144 km³, 0.63 Gt salt) and 6th (205 km³, 1.73 Gt salt), respectively, in the 21st century (see Table 1).

Table 1

Characteristics of the most voluminous SBIs in the 21st century in comparison with the 2023 SBIs¹.
Nr is the serial number in the sequence of the 21st century SBIs, arranged in descending order of the volume of water imported into the Baltic Sea. The calculation method is described in [4]

Time, yr (mo)	Nr	Volume, km ³			Salt, Gt [2]		
		Total	Sound	Belt	Total	Sound	Belt
2014.951 (DEC)	1	301.3	66.3	235.0	4.02	1.31	2.71
2015.840 (NOV)	2	233.3	51.3	182.0	2.46	1.02	1.44

¹ Major Baltic Inflow statistics from the website of Leibniz Institute for Baltic Sea Research Warnemünde. URL: <https://www.io-warnemuende.de/major-baltic-inflow-statistics-7274.html> (date of access: 11.02.2025).

Fin table 1

Time, yr (mo)	Nr	Volume, km ³	Salt, Gt [2]
		Total / Sound / Belt	Total / Sound / Belt
2003.011 (JAN)	3	228.3 / 50.2 / 178.1	3.02 / 1.27 / 1.75
2011.917 (DEC)	4	225.9 / 49.7 / 176.2	2.90 / 1.05 / 1.85
2008.783 (OCT)	5	211.4 / 46.5 / 164.9	1.89 / 0.89 / 1.00
2023.974 (DEC)	6	204.6 / 45.0 / 159.6	1.73 / 0.78 / 0.95
2023.757 (OCT)	26	143.9 / 31.7 / 112.2	0.63 / 0.57 / 0.06
2023.844 (NOV)	187	49.9 / 11.0 / 38.9	0.09 / 0.09 / 0.00
2023.899 (NOV)	207	42.5 / 9.4 / 33.2	0.14 / 0.14 / 0.00

The objective of this study is to reproduce characteristics and chronology of the 2023 SBIs and assess their impact on marine environment based on the NEMO (Nucleus for European Modelling of the Ocean) reanalysis [1].

2. Material and Methods

2.1. NEMO Reanalysis Data

The release of the latest version of the Baltic Sea reanalysis, NEMO-Nordic 2.0 [1], was used to compile the modelled time series of velocity components, u and v , temperature T , salinity S , and dissolved oxygen concentration O_2 with 1 day time step in the southwestern Baltic Sea for the period of 01.09.2023–20.02.2024. The model grid has 1 NM step in horizontal and 56 z-layers in vertical directions with approximately 1m thickness near the sea surface increasing to 24 m at 700 m depth. The model data were downloaded from E.U. Copernicus Marine Service Information [7].

2.2. Validation of NEMO model

To validate the reanalysis' ability in describing the long-term evolution of thermohaline and oxygen fields in the Baltic Proper caused by MBIs, the time series of the modelled vertical profiles of T , S , and O_2 in the Gotland Deep for the period of 1993–2024 were used. To facilitate the comparison with *in situ* measurements, the modelled vertical profiles were interpolated to (57°20'N, 20°03'E), the location of a monitoring station BY15 supported by the Swedish Meteorological and Hydrological Institute (SMHI).

The ability of the NEMO model to reproduce long-term evolution of thermohaline and oxygen fields in the Baltic Proper, caused by MBIs, is demonstrated in Fig. 2. The model fairly well reproduces shallowing of salinity and temperature contours in the permanent halocline and the increase of bottom salinity caused by 1993–1994, 1998, 2003, and especially 2014 MBIs, while the 2023 inflows did not result in any noticeable effect in the thermohaline fields. The oxygen concentration is poorly reproduced before 2022 and satisfactory after 2022. Remarkably that both observations and NEMO reanalysis reveal a positive trend in deep layer salinity and temperature increasing by approximately 1.5 g/kg and 2 °C, respectively, for the period of 1993–2024 (see Fig. 2).

2.3. Methods of calculation of water volume and salt mass for Baltic inflows

The water volume and salt mass imported to the Baltic Sea were calculated at a zonal transect across the Drogden Sill at 55.5915°N and a meridional transect across the Darss Sill at 11.9583°E (see Fig. 1). The water volume transport, $Q_B(t)$ and $Q_S(t)$ [m³/s], and the salt mass transport, $(Qsalt)_B$ and $(Qsalt)_S$ [kg/s], were calculated as

$$\begin{cases} Q_B = \iint u \cdot dy \cdot dz, \\ Q_S = -\iint v \cdot dx \cdot dz; \end{cases} \begin{cases} Qsalt_B = \iint u \cdot s \cdot \rho \cdot dy \cdot dz, \\ Qsalt_S = -\iint v \cdot s \cdot \rho \cdot dx \cdot dz, \end{cases} \begin{matrix} \text{Darss Sill} \\ \text{Drogden Sill} \end{matrix} \quad (4)$$

where u , v , s , and ρ are the daily mean values of velocity components [m/s], salinity [kg/ton], and water density [ton/m³]. The time series of $Q(t)$ and $Qsalt(t)$ were low-pass filtered using a 4th order Butterworth filter and the inflow events were defined as time intervals with positive terms of the filtered $Q(t)$ series.

Time series of inflowing water volumes, $V_B(t)$ and $V_S(t)$, and salt masses, $S_B(t)$ and $S_S(t)$, were derived from the time series of the transports, $Q_B(t)$ and $Q_S(t)$, in both channels as:

$$V(t) = Q(t) \cdot \Delta t, S(t) = Qsalt(t) \cdot \Delta t \text{ with } \begin{cases} V(t), S(t) = 0 & \text{for } Q(t) < 0, \\ V(t) = V(t), S(t) = S(t) & \text{for } Q(t) \geq 0. \end{cases} \quad (5)$$

For comparison, estimates of inflowing salt mass from Eq. (4), (5) were supplemented with that from the Mohrholz approach [4] (Eq. (1)–(3)).

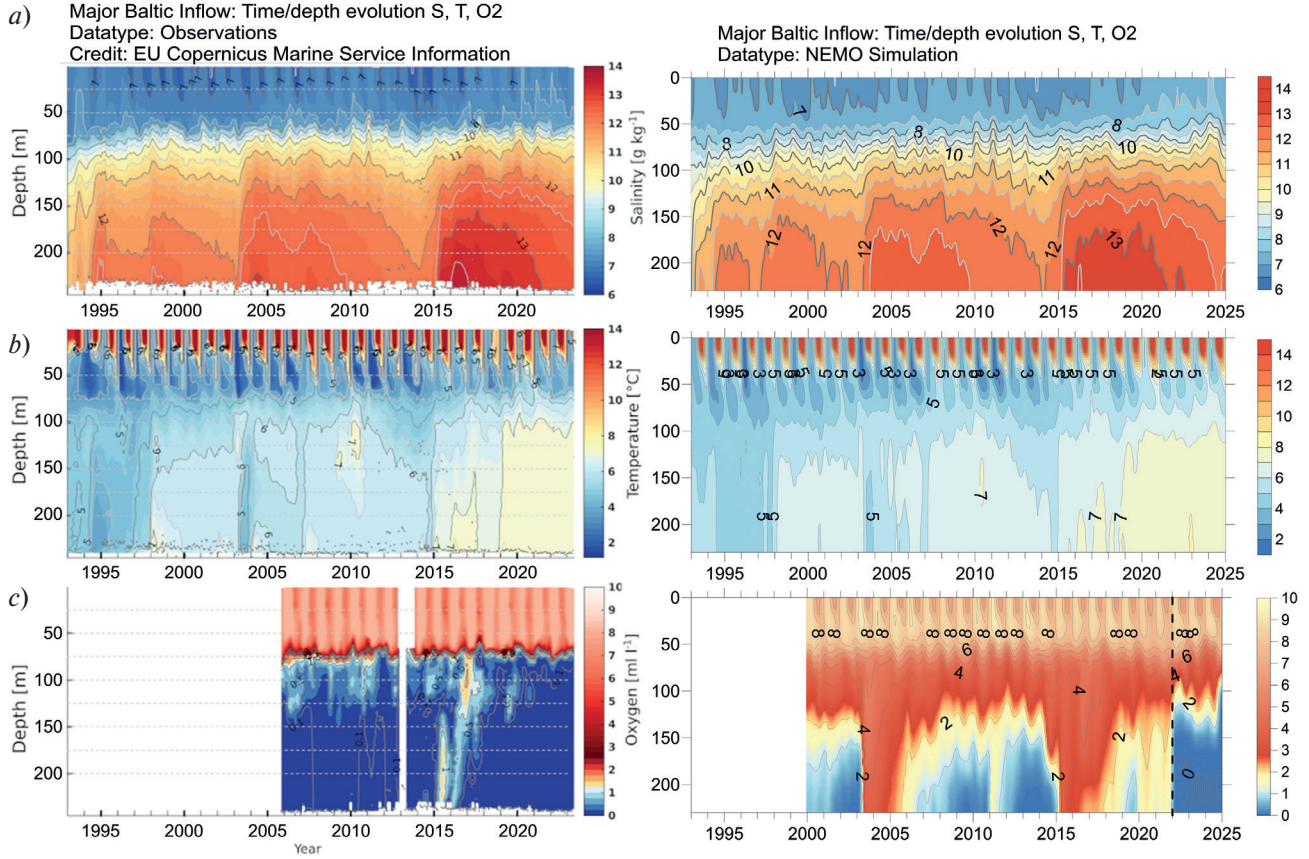


Fig. 2. Salinity (a), temperature (b), and oxygen (c) vs time and depth in the Gotland Deep for the period 1993–2024 according to observations at monitoring station BY15 (left) and NEMO reanalysis (right)

If two successive inflow periods, defined as time intervals with $Q(t) \geq 0$, were separated by a short interval $\Delta t < 3$ days with relatively small negative values $Q(t) < 0$, then the two inflow periods were considered a single inflow event. An additional requirement for a time interval with $Q(t) \geq 0$ to be considered as an SBI is an increase of bottom salinity above 14 g/kg somewhere within the interval.

3. Results

Time series of the water transport through the Darss and Drogden sills calculated from the NEMO reanalysis (Fig. 3) reveal 3 time intervals with positive Q_B and Q_S for a period from 20.09.2023 through 20.10.2023. The first interval, from 20.09.2023 through 26.09.2023, is characterized by a weak increase of surface salinity $s_{surface} < 12$ g/kg and therefore is not considered an SBI. The second and third intervals lasting from 29.09.2023 through 08.10.2023 and from 11.10.2023 through 17.10.2023, respectively, are characterized by a stronger surface salinity increase, $s_{surface} > 17$ g/kg, and are separated by a short interval $\Delta t < 3$ days with relatively small negative values of $Q(t)$. Therefore, they are considered a single SBI. For the same reasons two intervals with positive Q_B and Q_S in January–February 2024 are considered a single SBI too.

Both the approach [4] that explores historical data on the sea level and salinity and our approach which is based on the NEMO reanalysis data make possible to identify four SBIs for the period of September–December 2023 (see Table 2). Estimates of the SBI's volume obtained by the two approaches are

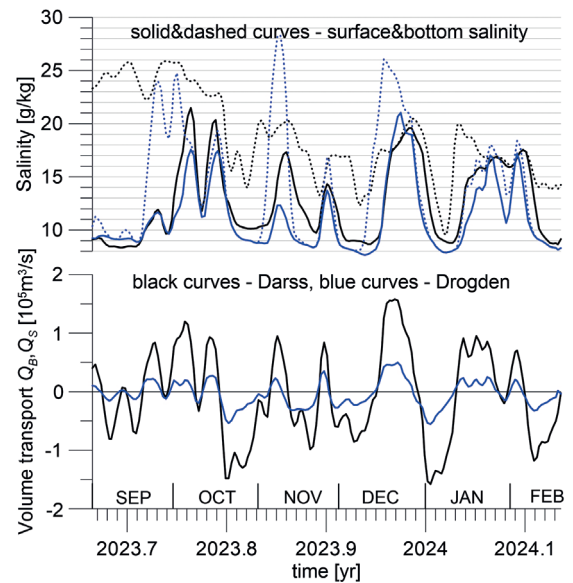


Fig. 3. Time series of water volume transports into the BS, Q_B , and Q_S , through the Darss and Drogden sills respectively (bottom), and salinity in the surface and bottom layers (top)

found to be extremely highly correlated with correlation coefficient of 0.998 at 95 % confidence limits of [0.923–1.000], and the mean value of the ratio of the Mohrholz [4] estimates to our estimates is 1.3. Estimates of salt mass imported to the BS with the SBIs obtained from different approaches display a weaker correlation than that of the SBIs water volumes (see Table 2).

Table 2

Characteristics of SBIs occurred in the period of 01.09.2023–20.02.2024 as estimated from NEMO reanalysis.
 To facilitate comparison of the NEMO estimates with that of [4], the latter are presented too (in bold text)

Time, yr	Volume, km ³ Total / Drogden / Darss	Salt, Gt, Eq. (4)–(5) Total / Drogden / Darss	Salt, Gt, Eq. (1)–(3) Total / Sound / Belt
2023.768 (29.09–17.10)	113.0 / 17.1 / 95.9 143.9 / 31.7 / 112.2	2.17 / 0.33 / 1.84	0.84 / 0.30 / 0.54 0.63 / 0.57 / 0.06
2023.853 (6–11.11)	39.2 / 6.1 / 33.1 49.9 / 11.0 / 38.9	0.58 / 0.11 / 0.47	0.00 / 0.00 / 0.00 0.09 / 0.09 / 0.00
2023.898 (23–27.11)	27.0 / 8.3 / 18.7 42.5 / 9.4 / 33.2	0.40 / 0.12 / 0.28	0.00 / 0.00 / 0.00 0.14 / 0.14 / 0.00
2023.972 (15–29.12)	172.9 / 39.0 / 133.9 204.6 / 45.0 / 159.6	2.95 / 0.80 / 2.15	1.20 / 0.68 / 0.52 1.73 / 0.78 / 0.95
2024.065 (13.01–06.02)	128.8 / 22.0 / 106.8	2.01 / 0.40 / 1.61	0.22 / 0.22 / 0.00

Vertical sections of salinity en route of Great Belt — Arkona Basin, Sound — Arkona Basin, and Arkona Basin — Bornholm Basin (Fig. 4) show that on 15.10.2023 and from 19.12.2023 to 28.12.2023 a vertically aligned salinity front between the North Sea water and the Baltic Sea water extended to the surface and was located between the Drogden Sill and the Darss Sill on one side and the Arkona Basin on the other side identifying the October and December 2023 SBIs. As a result, the saline water of the North Sea origin entered the Arkona Basin and accumulated there in the shape of a saline water dome. Remarkable that after the end of the December 2023 SBI on 29.12.2023, the saline inflow water did not flow further to the northeast to enter the Bornholm Deep but remained trapped in the in the Arkona Basin for a long while. It differs much from the October 2023 SBI when immediately after the end of inflow event the saline water accumulated in the Arkona Basin rushed northeast towards the Bornholm Deep causing an increase of bottom salinity there above 16 g/kg by 17.10.2023 (see Fig. 4).

Snapshots of bottom salinity and wind velocity maps in a transition zone between the North and Baltic seas and the southwestern Baltic Sea during the October and December 2023 SBIs are presented in Fig. 5 and 6. They will be discussed in next section.

4. Discussion and conclusions

This study is aimed to analyze SBIs occurred in the period 01.09.2023–20.02.2024 using the NEMO reanalysis data. To make sure that the model product adequately reproduces inflow events a modelled time series of salinity and temperature on depth and time of 32 yr long (1993–2024) were compared with the *in situ* measurements at a monitoring station BY15 located in the Gotland Deep. It was confirmed that the model quite accurately simulated evolution of temperature and salinity fields caused by Major Baltic Inflows (see Fig. 2). Moreover, the water volume imported to the BS with the 2023 SBIs being estimated from *in situ* observations of the sea level and salinity [4] was found to be highly correlated with the direct estimates from the NEMO reanalysis data (see Table 2).

Comparing characteristics of the October and December 2023 SBIs, it was admitted that the latter brought to the BS1.4–1.5 times more the water volume and salt mass than the former (see Table 2). However, further propagation of the inflowing water within the BS after October and December 2023 SBIs proceeded differently. Namely, immediately after the end of the October 2023 SBI the saline water accumulated in the Arkona Basin rushed northeast towards the Bornholm Deep causing an increase of bottom salinity there above 16 g/kg. To the contrary, after the end of the December 2023 SBI the saline water entered the Arkona Basin, accumulated there in the shape of a saline water dome, and acquired cyclonic rotation due to geostrophic equilibration in the bottom layer. The saline inflow water did not flow further to the northeast to enter the Bornholm Deep but remained trapped in the in the Arkona Basin for a long while being subjected to mixing with the above-lying less saline water. For this reason, the December 2023 SBI did not result in any considerable increase of bottom salinity in the Bornholm Deep (see Fig. 4).

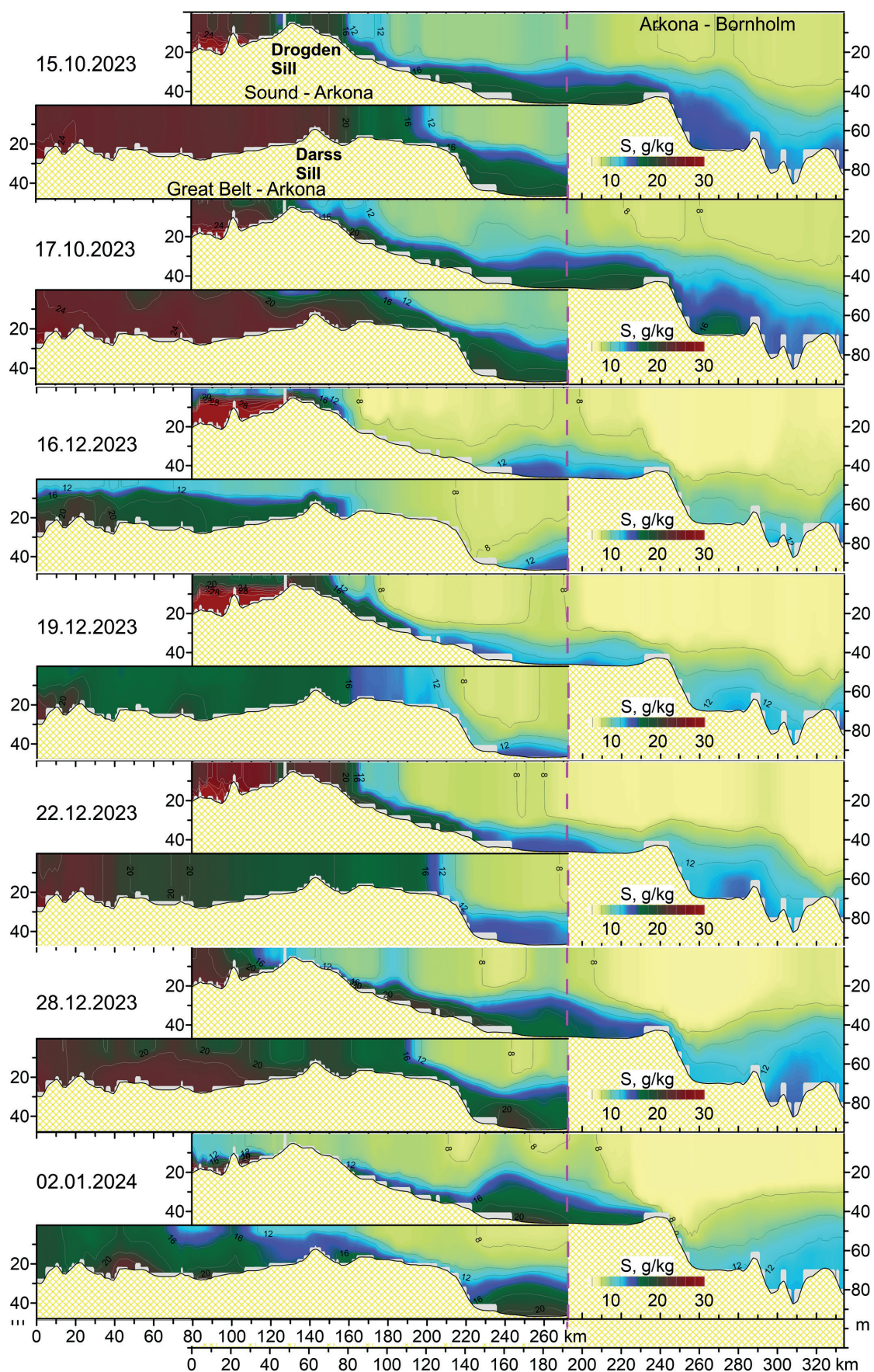


Fig. 4. Vertical sections of salinity en route of Great Belt — Arkona Basin, Sound — Arkona Basin, and Arkona Basin — Bornholm Deep during the October and December 2023 SBIs. The routes are shown in Fig. 1

To understand why the saline water entered to the Arkona Basin with the December 2023 SBI remained trapped there for a long while, let's address combined snapshots of bottom salinity and wind velocity in a transition zone between the North and Baltic seas and the southwestern Baltic Sea (Fig. 5 and 6).

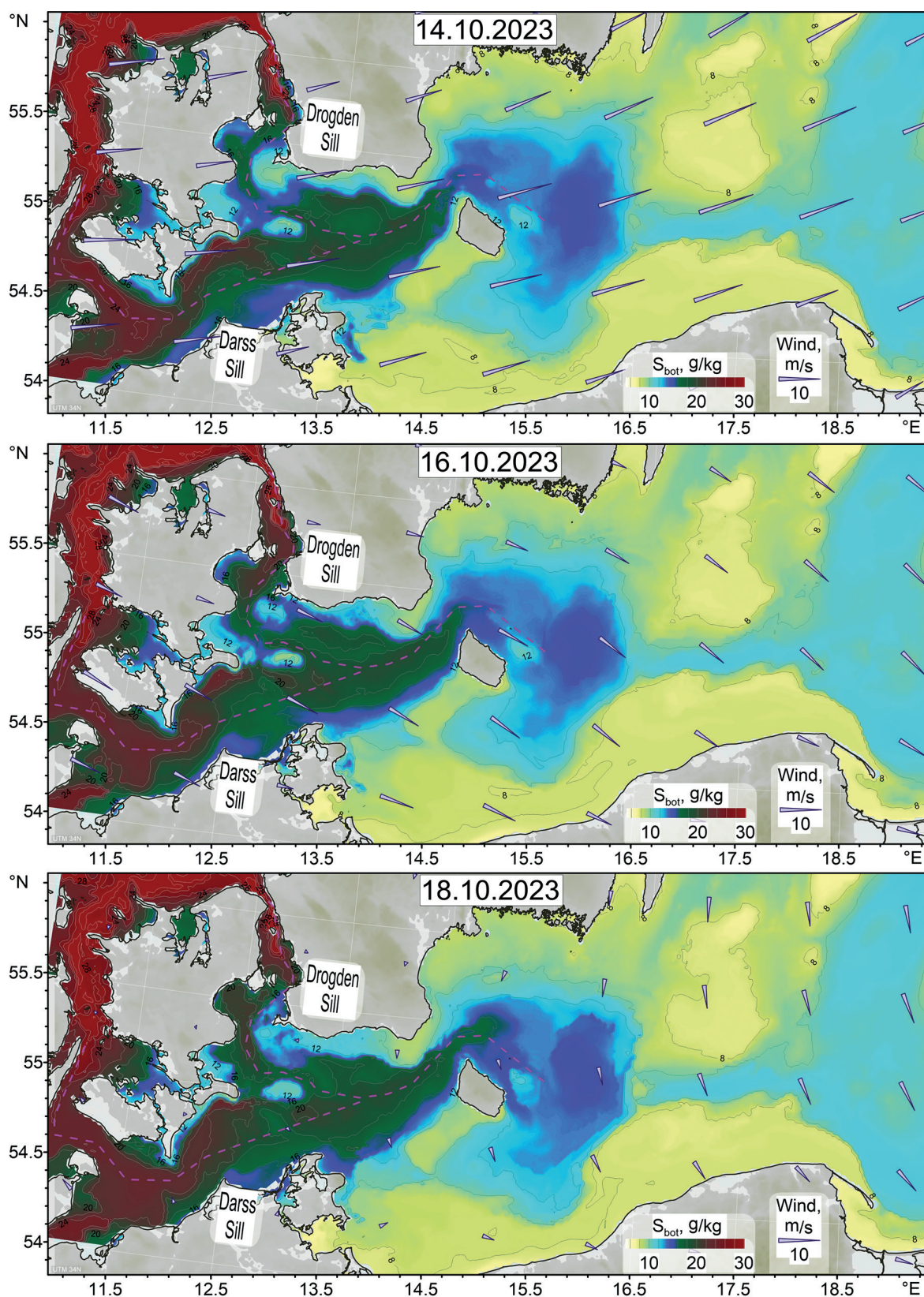


Fig. 5. Snapshots of bottom salinity (colors) and wind velocity vectors (elongated triangles) in a transition zone between the North and Baltic seas and the southwestern Baltic Sea during the October 2023 SBI

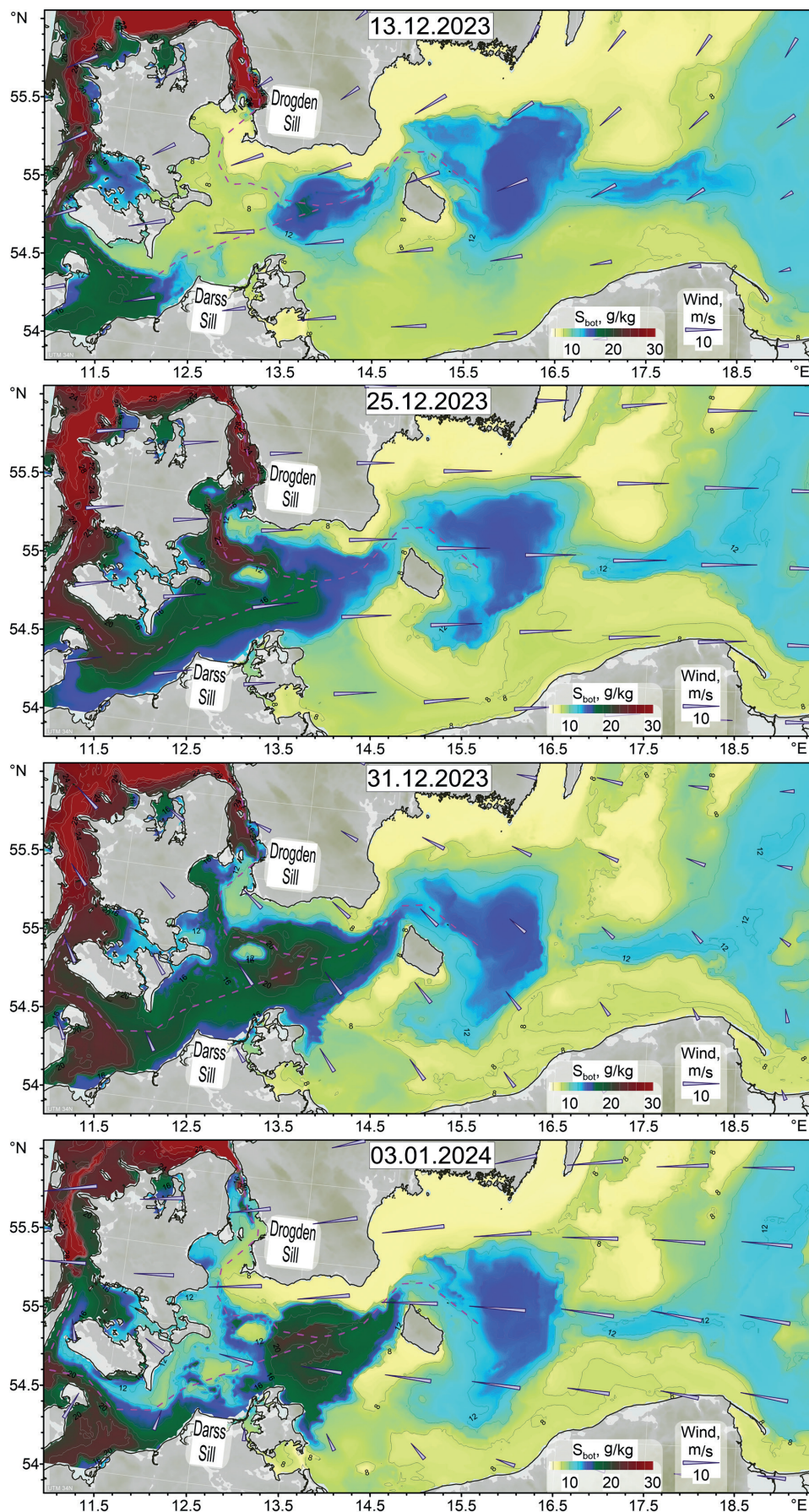


Fig. 6. Same as in Fig. 5 but for the December 2023 SBI

According to the Ekman transport dynamics, a strong westerly wind drove salty North Sea water south through the Belt and Øresund straits into the BS causing the October 2023 SBI (Fig.5, date 14.10.2023). After the October 2023 SBI, the wind changed for northwest causing the Ekman transport in the upper layer of the Bornholm Channel to the southwest, and the compensatory baroclinic current in the bottom layer towards the northeast. As a result, salty inflow water with $S > 16$ g/kg penetrated from the Arkona Basin into the Bornholm Deep through the Bornholm Channel (Fig. 5, date 16.10.2023).

Strong easterly wind drove the BS water through the Belt and Øresund straits towards the North Sea causing a drop of the sea level in the BS and thereby forming a favorable condition (preconditioning) for incoming December 2023 SBI (Fig. 6, date 13.12.2023). A strong westerly wind that followed drove salty North Sea water south through the Belt and Øresund straits back into the Baltic Sea causing the December 2023 SBI (Fig. 6, date 25.12.2023). After the December 2023 SBI, the wind changed to east-southeast causing the Ekman transport in the upper layer of the Bornholm Channel towards north-northeast and the compensatory baroclinic current in the bottom layer towards south-southwest. As a result, the salty inflow water remained trapped in the Arkona Basin and did not flow into the Bornholm Deep.

The comparison of the October and December 2023 SBIs revealed that the quantitative characteristics of an SBI, such as the imported water volume and salt mass, being important nevertheless do not fully determine the subsequent evolution of the salinity field in the remote basins of the BS. Apart from the imported water volume and salt mass the synoptic variability of the wind field over the BS is of paramount importance. Keeping in mind that salt water transport in the bottom layer of the Bornholm Channel, Słupsk Furrow, and Hoburg Channel towards the deepest BS basins is most intense at northwesterly, northerly and northwesterly winds respectively (Zhurbas and Väli, 2022), one may expect that a long-lasting northwesterly wind period immediately following the inflow event is the most favorable for ventilation of the BS deep layer.

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