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Fresh oxygen for the Baltic Sea — An exceptional saline inflow after a decade of stagnation

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ABSTRACT

The ecological state of the Baltic Sea depends crucially on sufficiently frequent, strong deep water renewal on the periodic deep water renewal events by inflow of oxygen rich saline water from the North Sea. Due to the strong density stratification these inflows are the only source for deep water ventilation. Since the early eighties of the last century the frequency of inflow events has dropped drastically from 5 to 7 major inflows per decade to only one inflow per decade. Wide spread anoxic conditions became the usual state in the central Baltic. The rare major Baltic inflow (MBI) events in 1993 and 2003 could interrupt the anoxic bottom conditions only temporarily. After more than 10 years without a major Baltic inflow events, in December 2014 a strong MBI brought large amounts of saline and well oxygenated water into the Baltic Sea. Based on observations and numerical modeling, the inflow was classified as one of the rare very strong events. The inflow volume and the amount of salt transported into the Baltic were estimated to be with 198 km^3 and 4 Gt, respectively. The strength of the MBI exceeded considerably the previous 2003 event. In the list of the MBIs since 1880, the 2014 inflow is the third strongest event together with the MBI in 1913. This inflow event will most probably turn the entire Baltic deep water from anoxic to oxic conditions, with substantial spread consequences for marine life and biogeochemical cycles.

1. Introduction

The Baltic Sea is a semi-enclosed sea in the humid zone of the northern hemisphere. Two narrow and shallow straits, the Belt Sea and the Sound (Fig. 1), connect the Baltic Sea to the North Sea, and thus to the world ocean. The restricted water exchange through the straits is of high importance for environmental conditions in the entire Baltic Sea (Elken and Matthäus, 2008; Matthäus et al., 2008). Due to the high fresh water runoff from the catchment area, outflow conditions are generally dominating. The salt balance of the Baltic is maintained by sporadic inflows of highly saline waters from the North Sea. Saline inflows can be of barotropic or baroclinic type. Barotropic inflows are forced by sea level differences between the Kattegat and the Arkona Basin, caused by wind and air pressure forcing (Franck et al., 1987; Wyrtki, 1954; Matthäus, 2006). These inflows may occur at any time of the year, although its probability is higher in the winter season, when the wind forcing is at its seasonal maximum. Baroclinic inflows usually occur during long calm periods in summer, and are driven by the salinity gradient between the Baltic and the Kattegat (Knudsen, 1900; Hela, 1944; Feistel et al., 2003a, 2003b, 2006; Mohrholz et al., 2006). The saline inflows maintain the brackish character of the Baltic waters, with mean surface salinity of about 7 and bottom salinities between 11 and 13 in the central basins. The residence time of saline water in the Baltic is about 30 years (Franck et al., 1987). The strong vertical stratification of the Baltic Sea blocks the direct ventilation of the deeper layers by deep convection during the winter and during storms. Only the layers above the permanent halocline at 60 to 70 m depth are in contact with the atmosphere and are directly supplied with oxygen. The deep water is renewed exclusively by lateral advection, namely by the eastward spreading of dense waters from saline inflow events. Thus, the oxygen content of the saline inflow waters is of crucial importance for the environmental conditions in the deep water. Oxygen content of inflowing water depends on the season when the inflows occur. In summer the oxygen concentration of inflowing water is reduced due to high temperatures and by oxygen demand of biogeochemical processes. In fact, summer inflows do not considerably contribute to the ventilation of deep water. Mainly inflows between October and March may supply oxygen to the deep Baltic basins. Further, an inflow needs a certain volume of saline water to reach the bottom layer of the central basins. Small inflows are soon diluted on their pathway toward the central Baltic.

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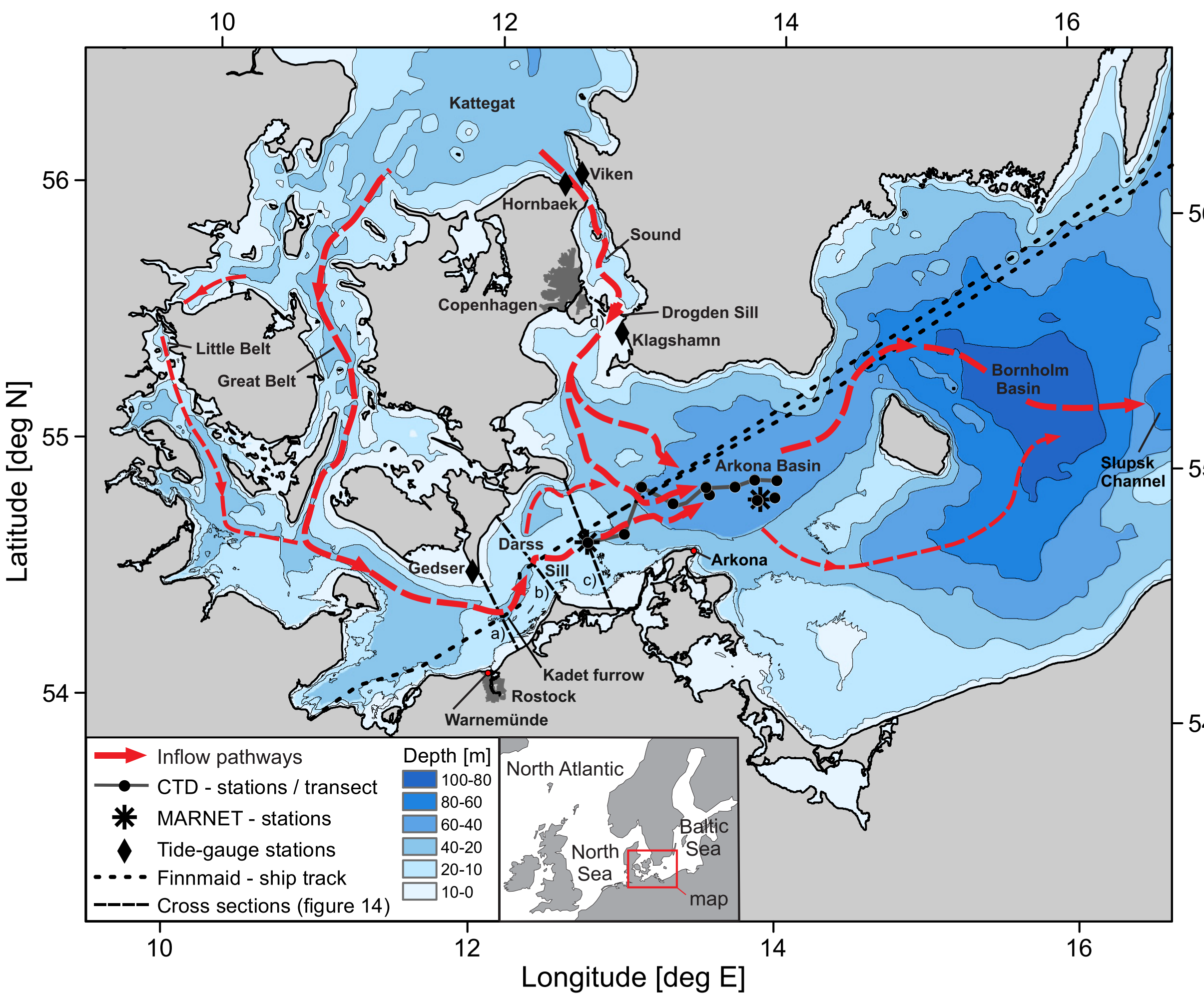

Fig. 1. Bathymetric map of the southwestern Baltic Sea with positions of the measurement sites. The pathways of inflowing highly saline water are indicated by dashed bold arrows. The black dashed lines depict the location of across channel sections of Fig. 14. The entire area is covered by the applied high resolution numerical model.

Thus, the density of the inflowing water is reduced and finally the water is sandwiched somewhere between the halocline and the denser bottom water.

1.1. Major inflow events

Inflow events, which carry enough saline water into the Baltic to reach the bottom of the central basins, are called major Baltic inflows (MBI). These are barotropic inflow events, forced by special conditions of the large scale atmospheric circulation over the North Atlantic and Europe (Lass and Matthäus, 1996; Schinke and Matthäus, 1998). The inflow is usually preceded by a phase of easterly winds lasting for approximately 1 month over the eastern North Sea and the Baltic. The water is piled up in the Arkona Basin and causes a barotropic pressure gradient toward the Kattegat. During this phase the outflow from the Baltic Sea is enhanced and exceeds considerably the fresh water runoff. Consequently, the mean sea level of the Baltic is sinking. The inflow phase starts when the wind forcing switches from easterly to westerly directions. Then the water level in the Kattegat is rising, whereas it is sinking in the Arkona Basin. The barotropic pressure gradient alters its direction and forces the inflow of Kattegat water into the Baltic. The persistence and intensity of the westerly wind mainly determine the intensity of the inflow and the amount of salt transported into the Baltic. To fill up the Sound and the Belt Sea with saline water it takes usually 2 to 3 days and 2 to 4 weeks, respectively. Thus, the inflowing saline water enters the Arkona Basin first through the Sound and with a delay of 1 to 3 weeks also through the Belt Sea, if the period of westerly winds persists long enough. According to Fischer and Matthäus (1996) a MBI can be divided into three characteristic periods. In the precursory period (PCP), just after the inflow has started and highly saline water enters the Arkona Basin exclusively via the Sound. The PCP lasts on average for about 22 days. It is followed by the main inflow period (MIP), when saline waters also overflow the Darss Sill. The duration of MIP is on average 10 days. When the inflow ceases at the Darss Sill, the post inflow period starts with decreasing sea level in the Baltic. The real inflow phase consists of the precursory period and the main inflow period. In our study of the 2014 MBI, a fourth period was added: the outflow period with easterly winds before the inflow phase starts. This phase is not well developed at each MBI, but for the strong 2014 event it was.

Franck et al. (1987) provided the first long term statistics for the occurrence and intensity of MBIs from 1897 to 1976. Their study is based on daily salinity measurements of the light vessel "Gedser Rev", located in the Darss Sill area. This position is placed at the eastern rim of the Belt Sea, the major of the two connections between the Kattegat and the Arkona Basin. Following the suggestion by Wolf (1972), Franck et al. (1987) used two major criteria to identify a barotropic inflow at the Darss Sill. First, the bottom salinity must be equal or exceeding 17. Secondly, the salinity stratification must be weak, expressed by a stratification coefficient G equal or below 0.2. Where G is defined as

$G = 1 -$ (surface salinity/bottom salinity). Both ensure a barotropic inflow process with highly saline water throughout the water column. These conditions must be persistent for at least five consecutive days to classify the inflow as a MBI. Using this scheme, Franck et al. (1987) derived an empirical intensity index Q_{FMS87}, which was defined by following Eq. (1):

$$Q_{FMS87} = 2k\,d^{-1} + 7.143\,S - 131.429. \quad (1)$$

Where k is the time span in days where the two above-mentioned criteria are fulfilled at the position of the light vessel "Gedser Rev", and S is the mean practical salinity over the same period. The index Q_{FMS87} has a range between zero and 100, which describes the largest possible MBI. Based on the Q_{FMS87} index it was shown that the MBIs occur exclusively between August and April, with a maximum in December. Maximum intensity and duration of inflows were observed between November and January. During their investigation period from 1897 to 1976 five to seven MBIs per decade were detected, which appear in groups interrupted by periods of 1 to 4 years without MBI.

The main weakness of the intensity index Q_{FMS87} was the lack of any observational information about the inflow process through the Sound. The volume transports between the Kattegat and the Arkona Basin are usually split between the Belt Sea and the Sound with a ratio between 70 to 30% (Jacobsen, 1980; Jakobsen and Trébuchet, 2000) and 80 to 20% (Mattsson, 1996). The real ratio may vary within this range, due to different forcing conditions of the particular inflow events. Thus, additional information from the Sound transport is needed to obtain a good estimate of the total Inflow volume and salt transport of an inflow.

Fischer and Matthäus (1996) reviewed the Q_{FMS87} with special focus on the Sound transports. They derived a new quantitative intensity measure Q_{FM96} (Eq. (2)). It is based on the total amount of salt M in giga tons, which is transported through the Belt Sea (M_B) and the Sound (M_S) into the Baltic Sea during an inflow event.

$$Q_{FM96} = \frac{M_S + M_B}{0.1\,Gt}. \quad (2)$$

To identify the inflow at the Sound two rules were introduced according to the criteria for the Darss Sill area. First: the surface salinity at the Sound must be equal or higher than 17, and the current must be directed into the Baltic Sea. Second: all days of the PCP (but not more than 15) and all days of the MIP, which meet first condition, must be taken into account for the transport estimations. To make the intensity index unitless, the mass of salt is divided by 10^{11} kg (=0.1 Gt).

The statistics of MBI was extended until 2006 by Matthäus (1993), Schinke and Matthäus (1998) and Matthäus et al. (2008). The frequency and intensity of MBIs changed drastically between 1976 and 1983. Long lasting stagnation periods without any MBI became the usual state in the deep basins. Only in 1993 (Dahlin et al., 1993; Jakobsen, 1995; Matthäus and Lass, 1995; Liljebladh and Stigebrandt, 1996) and in 2003 (Feistel et al., 2003b, 2006; Lehmann et al., 2004) MBIs were observed that were able to ventilate the deep Baltic basins for 1 to 2 years. Since 2003 only a weak MBI occurred in late autumn 2010 which transported about 1 Gt salt into the Baltic. However, this inflow was too weak to have significant impact on the conditions in the deep Baltic basins.

Beside the observational estimates of the volume and salt transport of the MBIs, several attempts were made to reconstruct the inflows in numerical models. For instance, Meier et al. (2003) estimated the inflow volume of high-saline water ($S > 17$) of the 1993 inflow as 137 km^3, which is close to the observations of 135 km^3 (Matthäus, 1993; Matthäus and Lass, 1995). Moreover, Meier et al. (2003) could also reproduce the nearly equal volume partitioning of the inflowing water between Darss Sill and the Sound.

Especially the 2003 inflow event has been used as a benchmark test. Lehmann et al. (2004) computed the total volume transport as 240 km^3. In contrast, Hofmeister et al. (2011) or Fu (2013) gave a lower transport value with 167 km^3 and 179 km^3 respectively. The spread of the model results around the estimation of 200 km^3, based on observations (Feistel et al., 2003b), shows that still an optimal modeling strategy is missing. Crucial are the horizontal resolution in the Danish Straits, due to their complex bathymetry, but also the choice of the vertical coordinate system (z-level, Lehmann et al., 2004, or terrain-following coordinates, Burchard et al., 2005, or Hofmeister et al., 2011).

The nutrient conditions in the Baltic Sea react strongly on the alternation between inflow and stagnation periods. This has been studied among others by Fonselius (1967, 1970), Nehring (1989), Nehring and Matthäus (1991) and Nausch et al. (2003). In the presence of oxygen, phosphate is fixed in the sediments and onto sedimenting particles as an iron-III-hydroxyphosphate complex (cf. Balzer, 1984). If the system turns from oxic to anoxic conditions, accompanied by the change of the redox potential, this complex is reduced by hydrogen sulfide (Hille et al., 2005). Phosphate and iron(II)ions are liberated leading to an increase in the phosphate and iron concentrations in the deep water. Moreover, inorganic nitrogen compounds are affected by the interplay between oxygen and hydrogen sulfide. Under oxic conditions, they are present almost exclusively as nitrate whereas nitrite is only an intermediate step of the nitrification. Under anoxic conditions, however, nitrate is denitrified to molecular nitrogen gas (N_2). Ammonium which is transferred from the sediments or liberated during mineralization processes, cannot be oxidized under these conditions and is enriched. Due to vertical mixing processes (Reissmann et al., 2009), enriched nutrients can be transported upwards and when reaching the euphotic surface layer, may determining to a large extent the intensity of primary production. However, looking from an ecosystem perspective, these vertical transports across pycnoclines are not sufficiently understood in time and quantity.

In this study we investigate the development and the dynamics of the exceptional MBI, observed in December 2014. This MBI has the potential to stop the stagnation period, which lasts since the 2003 MBI in the deep Baltic basins.

2. Material and methods

For the description of inflow dynamics and the transport calculations a data set from various sources was used. It consists of hydrographic and meteorological data from the permanent MARNET stations Darss Sill and Arkona Basin, sea level data from gauges at Landsort Norra, Hornbaek, Gedser, Viken and Klagshamn, surface temperature (SST) and surface salinity (SSS) observations from the ferry "Finnmaid", CTD and thermosalinometer data from the cruise EMB092 of R/V "Elisabeth Mann-Borgese" (15th–19th December 2014). The positions of the particular stations and measuring sites are depicted in Fig. 1. Additionally, meteorological data and topographic data from public sources were used. The data cover the time period from the 1st November to 31st December 2014.

2.1. The MARNET stations Darss Sill and Arkona Buoy

The first indications for the MBI 2014 were detected at the MARNET station Darss Sill. For this study, time series of wind, current and salinity at the Darss Sill and in the central Arkona Basin were obtained from two permanent autonomous stations of the German Marine Monitoring Network (MARNET). Both stations, Darss Sill and Arkona Basin (Fig. 1), are developed and operated by the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) (Krüger, 1997, 2000). The main purpose of the stations is the permanent observation of meteorological and hydrographic parameters for the environmental monitoring of the Baltic Sea, with special focus on the water exchange between the North and Baltic Seas (BSH, 2014).

The MARNET station Darss Sill (54°42′N, 12°42′E) is located at the transition between the Belt Sea and the Arkona Basin, 25 km east of the real topographic Darss Sill. The station consists of a bottom mounted, buoyancy stabilized pole as mounting platform for the sensors. Wind speed and wind direction are measured 10 m above the sea surface. Temperature and salinity measurements are performed at six depth levels in 2, 5, 7, 12, 17, and 19 m depths with SeaBird SBE 37 thermosalinometers. Additionally, in 7 and 19 m depths oxygen optodes are mounted. Current speed and direction is measured between 2 m and 20 m depth by a bottom mounted, upward looking ADCP (RDI WH 600 kHz) with 1 m vertical resolution.

The MARNET station Arkona Basin (54°53′N, 13°52′E) is positioned at the southern rim of the central Arkona Basin in the main pathway of eastward spreading saline inflows. The station is constructed as a semi diving spar buoy, fixed with two heavy anchors at the sea floor. The equipment consists of various meteorological and oceanographic sensors, similar to the station Darss Sill. For our study we used only the temperature and salinity observations, which are performed in eight depth levels at 2, 5, 7, 16, 25, 33, 40, and 43 m depths with SeaBird SBE 37 thermosalinometers.

Real-time data of both stations are transmitted hourly to BSH and IOW via METEOSAT and GSM. The real-time data of these stations enabled the exact temporal and first quantitative identification of the actual salt water inflow.

2.2. Sea level data

The tide-gauge data of the Swedish stations Landsort Norra, Viken and Klagshamn are provided by the online-data-server of the Swedish Meteorological and Hydrological Institute (SMHI, 2015). The data are related to the Swedish reference level RH2000, and were converted into mean sea level (MSL) by annual varying local factors because of the postglacial isostatic uplift of Scandinavia. These factors are for Landsort Norra −10.4 cm, Viken −7.5 cm and Klagshamn −12.58 cm, calculated after SMHI (2014) for the year 2014. The sea level at Landsort Norra, in the south of Stockholm, represents the mean filling level of the Baltic Sea (Feistel et al., 2008; Jacobsen, 1980; Lisitzin, 1974). The sea level gauges Viken and Klagshamn located in the north and south of the Sound are used to estimate the inflowing volume by tide-gauge differences.

For the Danish tide-gauge stations at Hornbaek and Gedser the data were extracted from the website of the Baltic Operational Oceanographic System (BOOS, 2014). The data is listed in hourly means and provided in MSL as reference level. These stations show the inflow activity of the Great Belt. All sea level data time series have temporal resolution of 1 h.

2.3. “Finnmaid” ferry data

The Finnish cargo ferry “Finnmaid” commutes regularly at 2 day intervals between Lübeck and Helsinki. On its 1100 km long track it crosses nearly the entire Baltic from the southwestern corner to the Gulf of Finland in the northeastern part. In frame of the Alg@line project in 2007 the ferry was equipped by the Finnish Marine Research Centre (SYKE) with a ferrybox system. It measures a continuous time series data of temperature, salinity, chlorophyll-a fluorescence and turbidity in surface water. In cooperation with the IOW the system was extended with a sensor for carbon dioxide partial pressure (pCO_2). The scientific equipment is regularly maintained when the ferry stays in Lübeck port. The temperature and salinity data of November and December 2014 were used to observe the temporal development of the surface salinity front from the Kadet Furrow toward the Arkona Basin. The spatial resolution of the temperature and salinity data is about 200 m.

2.4. Hydrographic data from cruise EMB092

From 15th to 19th December 2014, the German research vessel “Elisabeth Mann-Borgese” performed one of its regular cruises in the western Baltic. The main focus of the cruise was the maintenance of the MARNET stations Arkona Basin and Oder Bank, and on testing of new scientific equipment. Beside these tasks 15 CTD profiles were measured at 11 stations in the area of the central Arkona Basin to the Darss Sill from 17th to 19th December (see Fig. 1), to obtain information about the initial inflow phase in the southwestern Baltic. The CTD system consists of a SeaBird 911+ probe, mounted on a sampling rosette. It was equipped with 13 free flow tubes of 5 L volume which allow direct water sampling during the downward moving process. The CTD probe had double sensors for each parameter and was calibrated in the IOW laboratory. The data quality was cross checked by additional temperature measurements, and laboratory analyses of salinity and oxygen samples taken with the water sampler. After validation the remaining uncertainties of the main parameters temperature, salinity and oxygen amount to 0.005 K, 0.006 and 4 μmol l^{-1}, respectively. The CTD winch had a newly developed swell compensation system controlled by motion sensor signals of the vessel to prevent vertical loops during profiling.

The CTD data were used to obtain characteristic properties of the two saline water bodies that entered the Arkona Basin via the Great Belt/Darss Sill and the Sound. The depth of the salinity 17 isohaline was identified as upper boundary of the Great Belt/Darss Sill water. The boundary of this water mass to the Sound water was determined by salinity of 21, and higher turbidity values. The estimated limits were used to model these surfaces for the area covered by the CTD profiles. Rectangular grids of 500 m grid point distance were generated by geostatistical methods (kriging with semi-variogram analysis) using the software tool SURFER. In addition with a grid of the seafloor, obtained from the iowtopo2_rev3 dataset (Feistel et al., 2008; Seifert et al., 2001), volumes of the different inflow water bodies were calculated for covered area. With an extrapolation of these data, the total inflow volume was estimated for the entire Arkona Basin.

The RV “Elisabeth Mann Borgese” is equipped with a thermosalinograph, which continuously collected temperature and salinity data of the surface water. These data were used to complement the surface data recorded by the “Finnmaid” ferry.

2.5. Baltic topography

The bathymetric dataset “iowtopo2_rev3” compiled by Seifert et al. (2001) is the most dense, quality checked and freely available dataset for the entire region of the Baltic Sea. This data set was used to generate regular grids of different resolutions (250 m, 500 m grid point distances) for the western Baltic by the same geostatistical methods as described above. Also the topographic information in Fig. 1, the data about the cross sections at Darss Sill and Sound, and the volume calculations for the basins are based on this bathymetric dataset.

2.6. Transport estimates

For the calculations of transports through the straits between Kattegat and Arkona Basin, namely the Sound and the Belt Sea, different methods were applied.

The total transport between Kattegat and the Baltic for time scales longer than 3 days can be derived from the change of water volume in the Baltic. The volume change of the Baltic was estimated using the sea level change at Landsort Norra in the western Gotland Basin. This sea gauge is located closely to the node lines of the main seiche modes of the Baltic and represents its filling state (Feistel et al., 2008; Jacobsen, 1980; Lisitzin, 1974). Thus, the effect of seiches is very little on this sea gauge. To exclude the residual impacts of short term fluctuations a fourth order low pass Butterworth filter with 3-day cut off period was applied to the original data. Seiches with a typical period of 25 h or less (Jönsson et al., 2008; Wübber and Krauss, 1979), as well as the impact of short term meteorological patterns are removed. The volume change of the Baltic was estimated using Eq. (3).

$$\Delta V = 3.8\ km^3 cm^{-1} * \Delta\eta - 1.3\ km^3 d^{-1} * \Delta t. \tag{3}$$

Where ΔV is the volume transport through the Danish straits in km^3, $\Delta\eta$ is the sea level change at Landsort Norra in cm, and Δt is the time span of sea level change in days. This equation includes the mean climatological freshwater surplus from runoff and precipitation of 1.3 km^3d^{-1}. The sea level is measured in whole centimeters. Thus, the uncertainty of sea level change for a certain period is 1 cm in the beginning plus 1 cm in the end. The uncertainty of 2 cm in sea level change results in an uncertainty of 8 km^3 in volume change. The total transport estimated with the sea level change at Landsort Norra splits into the two pathways via the Sound and the Darss Sill.

Fischer and Matthäus (1996) derived an empirical relation for the split of transport between Sound and Belt Sea from an analysis of about 90 MBI events between 1880 and 1976. They found that during the PCP and the first 5 days of the MIP the distribution of volume transport between the Darss Sill (V_{DS}) and the Drogden Sill (V_{DR}) is close to Eq. (4).

$$V_{DR} = 0.326\ V_{DS} \quad (r = 0.991). \tag{4}$$

The inflow at the Drogden Sill stopped usually at day five of the MIP. Afterwards an outflow is observed at the Drogden Sill, whereas the inflow at the Darss Sill continued. The outflow at the Drogden Sill from day five of the MIP onwards was estimated with:

$$V_{DR} = -0.115\ V_{DS} \quad (r = 0.958). \tag{5}$$

We applied Eqs. (4) and (5) to the total transport, derived from the sea level change at Landsort Norra to obtain an estimate for the Darss Sill and the Drogden Sill transport.

A second method to estimate transports in the connecting straits between Kattegat and the Arkona Basin is based on local sea level differences $\Delta\eta$. In the first approximation the flow through the straits is driven by the along channel barotropic pressure gradient, which is balanced by the friction in the channel. Usually a quadratic frictional law (Eq. (6)) is applied, with a flow resistance coefficient K (e.g. Jacobsen, 1980; Omstedt, 1987).

$$\Delta\eta - A = K_f Q|Q|. \tag{6}$$

Q is the transport through the channel, and A is an empirical correction factor the baroclinic pressure gradient. Some studies include this correction into the empirical flow resistance coefficient.

A further linear term can be introduced into Eq. (6) to account for the geostrophic adjustment of the channel flow (Mattsson, 1996).

$$\Delta\eta - A = K_1 Q + K_f Q|Q| \quad \text{with} \quad K_1 = \frac{f}{gH} \quad \text{and} \quad K_f = \frac{c_D L}{gH^3 W^2}. \tag{7}$$

The factors K_1 and K_f can be derived from the theory of channel flow. Usually, K_f is adjusted to the observed transport by fitting the drag coefficient c_D. H, L and W are the mean depth, length and width of the channel. Here f and g are the inertial frequency and the earth acceleration.

Both equations were applied. However, the difference of about 3% for the Sound is rather small. The uncertainty of the method is given by Mattsson (1996) with approximately 10%. Thus, we used finally the simple quadratic equation with $K_f = 2.03 * 10^{-10}\ s^2m^{-5}$, and $A = 0.018$ m for the Sound which is also in the range of K_f from $1.6 * 10^{-10}\ s^2m^{-5}$ to $2.6 * 10^{-10}\ s^2m^{-5}$ given by Jakobsen et al. (1997).

The application of the same equation to the Belt Sea transports is also possible and often done, but it results in higher uncertainties than for the Sound. Due to the greater water depth of the Belt Sea the impact of the baroclinic pressure gradient between the Kattegat and the Arkona Basin is considerably higher. It has been shown by earlier studies that the resistance coefficient K_f depends on the stratification in the Belt Sea. Mean values for the resistance coefficient were given by Pedersen (1978) with $K_f = 4.0 \cdot 10^{-11}\ s^2/m^5$, and Jacobsen (1980) with $K_f = 3.8 \cdot 10^{-11}\ s^2/m^5$. Recent investigations from Jakobsen et al. (2010) suggest a minimum resistance coefficient for the entire Belt Sea between 2.0 and $3.0 \cdot 10^{-11}\ s^2/m^5$. For the transport estimates in this study a resistance coefficient of $2.5 \cdot 10^{-11}\ s^2/m^5$ was used, since during a MBI the flow through the Belt Sea is mainly barotropic and the resistance coefficient should be close to the minimum.

The transport estimations described above are indirect methods. The volume and salt transports at the Darss Sill were also estimated from direct current and salinity measurements of the MARNET station Darss Sill. Badewien (2002) has shown that the transports calculated for the vertical profile at this measuring site provide a good estimate for the entire section Darss Sill. For this purpose the current and salinity data were extrapolated horizontally and weighted with the width of the cross section at each depth level. However, we found that the extrapolation method according to Badewien (2002) results in a significant overestimation of transports. Thus, the calculated transports were calibrated with the total volume change of the Baltic, derived from sea level change at Landsort Norra, and corrected for the Sound transports. For this calibration we used the period with rapid rising sea level from 3rd December to the 18th December 2015. The correction factor was determined with $c_{DS} = 0.79$. For the Sound no current measurements are available for the measuring period. Thus, the two indirect methods were used to estimate the transports there.

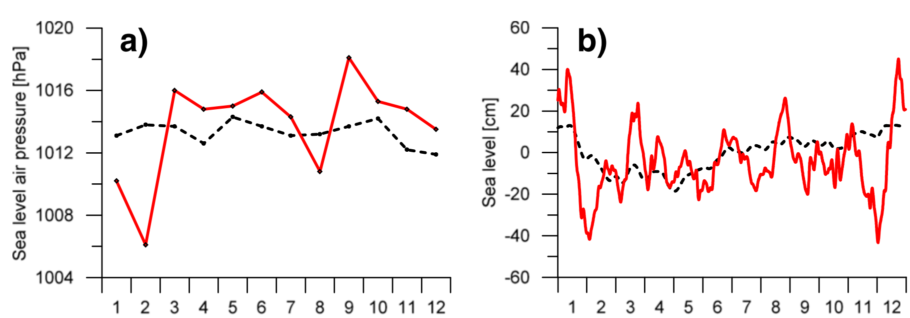

Fig. 2. a) Monthly mean of sea level air pressure at station Warnemünde in 2014 (solid red line) compared to the climatological mean 1947–2005 (dashed black line), data from DWD (2015). b) 3 days mean values of sea level at station Landsort Norra in 2014 (solid red line) compared to the mean of the 10 year period 2005–2014 (dashed black line).

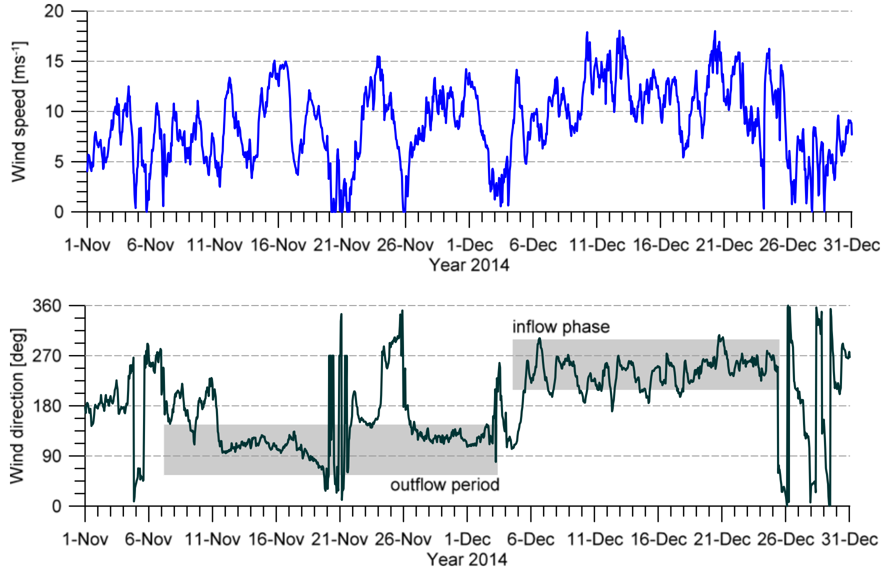

Fig. 3. Wind forcing in the western Baltic during November/December 2014. Data were obtained from the MARNET station Darss Sill.

2.7. Numerical model

Finally, we estimated the volume and salt flux through the cross-sections at Darss Sill and the Drogden Sill with the help of a numerical model. The model provided hourly mean values of velocity and salinity at every grid point. Thus, the model provided also a direct estimate of the fluxes. We employed the General Estuarine Transport Model (GETM) in a multi nested downscaling framework. GETM is a 3D free-surface primitive equation model using the Boussinesq and boundary layer approximations. Vertical mixing is parameterized by means of a two-equation k- turbulence model coupled to an algebraic second-moment closure. Advection of momentum, turbulent kinetic energy, and dissipation rate was done by a third-order scheme and for tracer by a second-order scheme (Klingbeil et al., 2014). The model has been successfully applied to simulate inflow events into the Baltic Sea (Burchard et al., 2005), and was further used for climate downscaling and a statistical analysis of inflows in the western Baltic Sea (Gräwe et al., 2013).

For the present setup, we discretized the model domain with a horizontal resolution of 1/3 nautical mile (app. 600 m). The model domain covers the Danish Straits and the western Baltic. The open boundaries are located along 57°N in the Kattegat and along the 17°17.5′E meridian at the eastern rim of the Bornholm Basin. In the vertical we used 50 terrain-following adaptive layers, with a zooming toward stratification and a minimum layer thickness of 0.3 m. Except the increase in vertical resolution, the present setup is identical to the one used by Klingbeil et al. (2014). A detailed description and validation of the used setup is given in Klingbeil et al. (2014).

At the open boundaries of the model domain, the water elevations, depth averaged currents, as well as salinity and temperature profiles are prescribed. This external forcing was taken from a model of the North Sea–Baltic Sea (NSBS) with a horizontal resolution of 1 nautical mile and 50 vertical layers. To account for large scale variations and storm surges, NSBS was nested into a depth-averaged storm surge model of the North Atlantic with a resolution of 5 nautical miles.

The atmospheric forcing was derived from the operational model of the German Weather Service with a spatial resolution of 7 km and temporal resolution of 3 h. The initial conditions for the model were taken from a running simulation, starting at the 1st January 2014.

3. Results

The MBI 2014 was forced by the typical meteorological sequence described in previous studies (Lass and Matthäus, 1996; Schinke and Matthäus, 1998). During autumn, September to November 2014, central Europe and the Baltic Sea area were mainly influenced by high pressure systems located over northeastern Scandinavia to eastern Europe and low pressure systems over the northeast Atlantic. The sea level air pressure anomaly at Warnemünde was positive from September to December 2014 (Fig. 2a).

Consequently, the wind situation was abnormally calm for this season with mostly SE, S to SW directions. The mean wind speed from

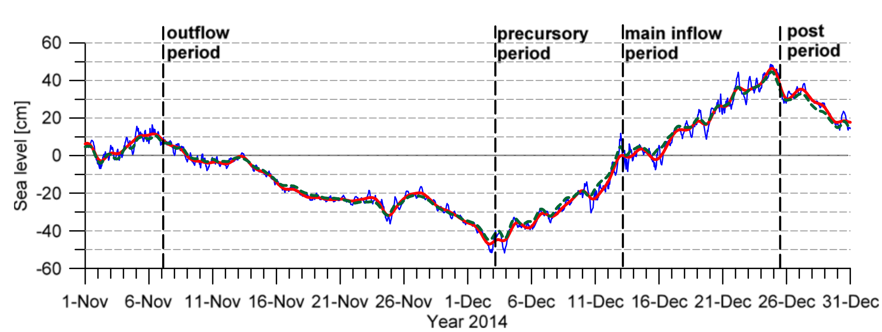

Fig. 4. Observed hourly sea level at Landsort Norra (thin blue line) and low pass filtered time series, using a cutoff period of 3 days (bold red line). The dashed green line depicts the sea level at Landsort Norra from the numerical model.

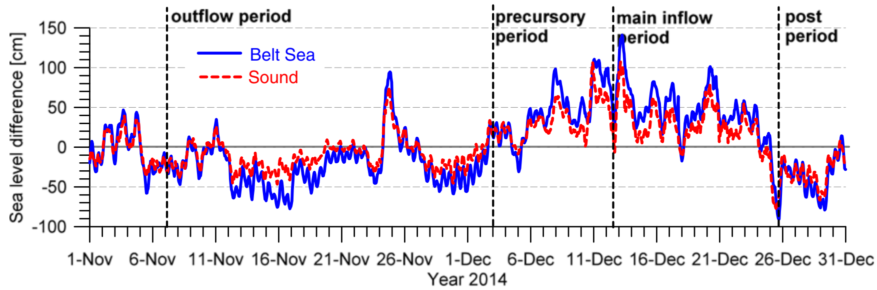

Fig. 5. Sea level difference between Kattegat–Arkona Basin. Through the Belt Sea (Hornbaek–Gedser, solid blue line) and through the Sound (Viken–Klagshamn, dashed red line).

September to November 2014 was only 3.9 ms^{-1} at the station Warnemünde. At the station Arkona, which is located on a high cliff 42 m above mean sea level, the average wind speed from September to November 2014 was 6.1 ms^{-1}. There daily means of wind speed were not exceeding 12 ms^{-1}. Hourly means higher than 10.7 ms^{-1} (>5 Bft) were seldom with around 6.5% of the time and show a maximum of 16 ms^{-1} in these months. The wind speed was weak to moderate, lower than 7.9 ms^{-1} (4 Bft) in 72.5% of the time. Arkona, in the north of Rügen island, is the windiest station along the German North and Baltic Sea coast (Lefebvre and Rosenhagen, 2008) and shows more or less the situation at the open water in the southwestern part of the Baltic Sea. In comparison, the coastal station Rostock–Warnemünde recorded wind speeds higher than 10.7 ms^{-1} in only 1.9% of this timespan and 94.6% of the data had values below 7.9 ms^{-1}. This long period of calm wind forcing and high air pressure resulted in a lowered mean sea level of the Baltic Sea. Since the beginning of September the mean sea level showed values below zero at the Swedish Landsort station in the central Baltic (Fig. 2b). Only a short phase of southwest–west winds from 19th–29th October caused by low pressure systems up to 970 hPa over northern Europe and a long lasting high pressure area, spreading from western to eastern Europe, pushed the sea level at Landsort to positive values up to 12 cm above mean sea level. This mainly calm weather situation of autumn 2014 is matching the inflow scenarios of Lass and Matthäus (1996) as well as Schinke and Matthäus (1998). They described that a positive air pressure anomaly in autumn and a resulting lowered mean sea level of the Baltic Sea often coincide with the occurrence of MBIs in the following winter season.

Between the 11th November and the first week of December 2014 medium to strong easterly winds with average speed of 8.8 ms^{-1} were observed in the western Baltic (Fig. 3). The east winds forced an outflow of Baltic surface water, followed by a drop in mean sea level in the Baltic (Fig. 4). The long lasting phase with easterly winds was interrupted only for a few days between the 23rd and the 26th November 2014. On the 2nd December the easterly winds calmed down for about 2 days. This stopped the outflow from the Baltic and the further drop in sea level. An onset of persistent westerly winds occurred on the 5th December. During the following days the wind speed increased to about 10 ms^{-1} and more. The resulting uplift of water in the eastern North Sea and Kattegat and the corresponding local drop of sea level in the Arkona Basin caused a steep barotropic pressure gradient between the Kattegat and the Arkona Basin. This pushed a strong barotropic inflow of saline North Sea water into the Baltic Sea. The heavy westerly winds lasted until the 25th December. The average wind speed during the inflow phase was 11.4 ms^{-1}. After the 25th December the wind speed decreased rapidly to about 5 ms^{-1} with changing directions.

According to the observed sea level at Landsort Norra (Fig. 4) the different phases of the inflow were identified. The outflow period started on the 7th November with a sea level of +10 cm. Afterwards the sea level was decreasing continuously, only interrupted by a short increase around the 26th November. The outflow period finished on 3rd December, when the minimum sea level of −47 cm was reached. Afterwards the inflow phase started with the precursory period with rapidly rising sea level. The inflow phase, consisting of the precursory and the main inflow period, lasted until the 25th of December. Then the maximum sea level of +48 cm was reached at Landsort Norra, and the post inflow period started with decreasing sea level. Fig. 4 also indicates that both, the filling state of the Baltic Sea and the dynamics of sea level patterns, are well reproduced by the numerical simulations.

The local sea level difference between the Kattegat and the western Arkona Basin is the driving force for the barotropic water exchange through the Belt Sea and the Sound. The sea level differences for the Belt Sea and the Sound were calculated from the tide gauges at Hornbaek and Gedser, and Viken and Klagshamn respectively (Fig. 5). Generally, the behavior at both channels is very similar. During the outflow period the sea level difference is negative, with mean values of −22.6 cm for the Belt Sea and −10.5 cm for the Sound. Only during the short interruption of easterly wind forcing around the 25th November

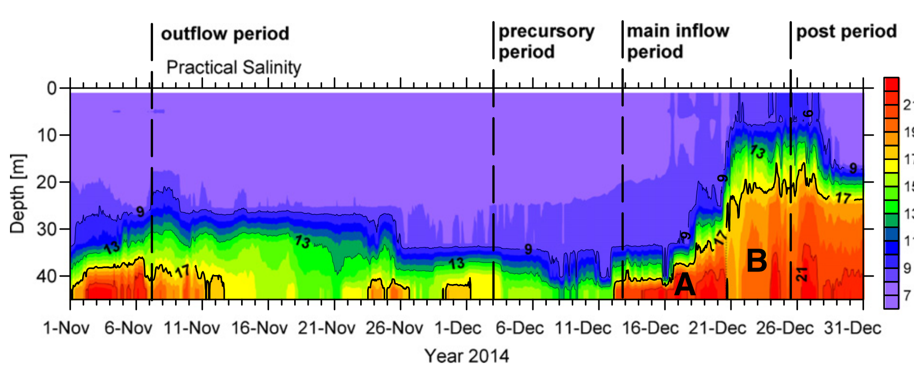

Fig. 6. Salinity at the MARNET station Arkona in November/December 2014. A — first saline overflow from the Sound, B — saline water from the Darss Sill.

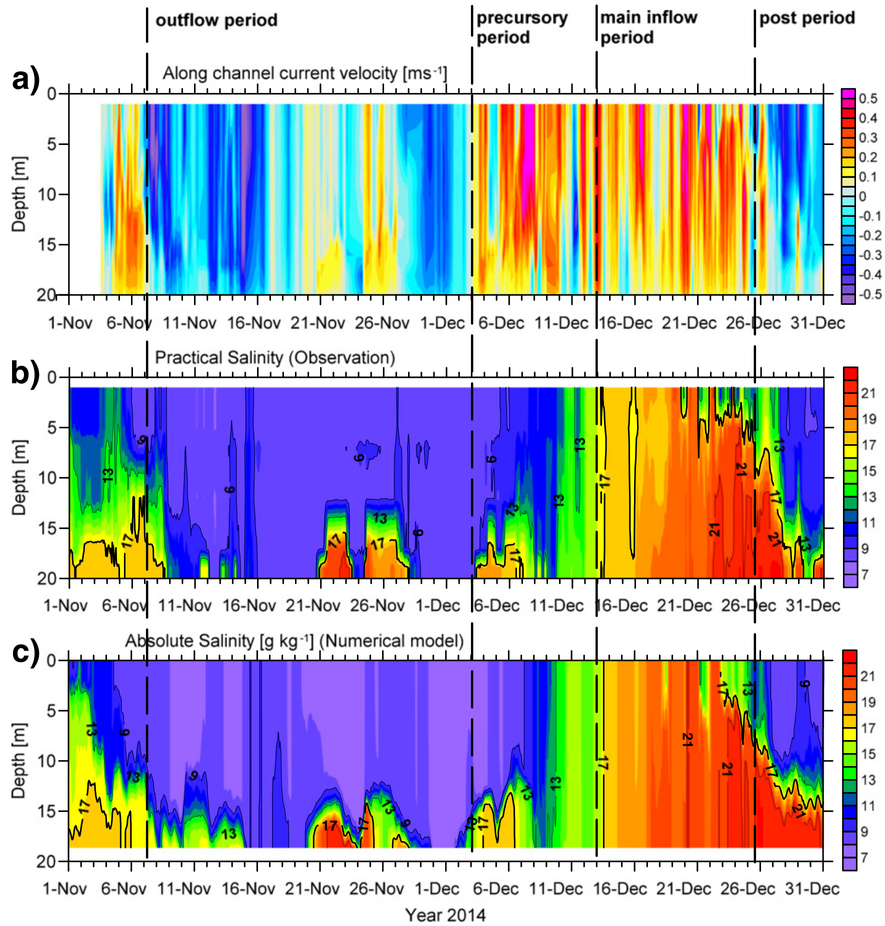

Fig. 7. Observations of along channel velocity (a) and salinity (b) at the MARNET station Darss Sill in November/December 2014, compared with salinity from numerical model (c) at the same position.

where positive sea level differences were observed. During the inflow phase the sea level differences changed their sign and increased considerably. For the Belt Sea and the Sound the mean sea level differences amount to +44.9 cm and +32.4 cm in the precursory period, and to +47.9 cm and +28.7 cm in the main inflow period. With the beginning of the post period the sea level differences dropped again to negative values.

Due to the shorter channel length, first highly saline water entered the Arkona Basin via the Sound around the 4th December. Unfortunately, there are no direct measurements from the Sound. However, at the MARNET station Arkona the first inflow water was detected on 12 December (Fig. 6), one day before the saline waters arrived at the Darss Sill (cf. also Fig. 7b). The salinity of this water mass increased in the following days to maximum values of about 22.6, observed 2 m above the bottom on 15th December.

The advection time of inflowing water from the Drogden Sill to the MARNET station Arkona of approximately 8 days was very well in agreement to earlier observations (Lass and Mohrholz, 2003; Burchard et al., 2005; Sellschopp et al., 2006). On its pathway the entrainment of ambient brackish water lowered the salinity of the inflowing water. Thus, the salinity at the Sound was assumed to be well above 23. This was also supported by the direct CTD observations that revealed bottom salinities of 25 in the western Arkona Basin on 18th December.

The time series data from the Darss Sill station supplied a comprehensive picture of the inflow process via the Belt Sea (Fig. 7). The outflow period from 7th November to 3rd December is characterized by

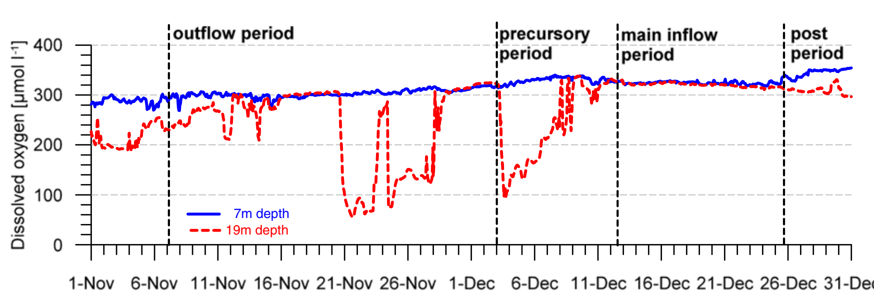

Fig. 8. Time series of oxygen concentration at the MARNET station Darss Sill in 7 m (solid blue line) and 19 m depth (dashed red line).

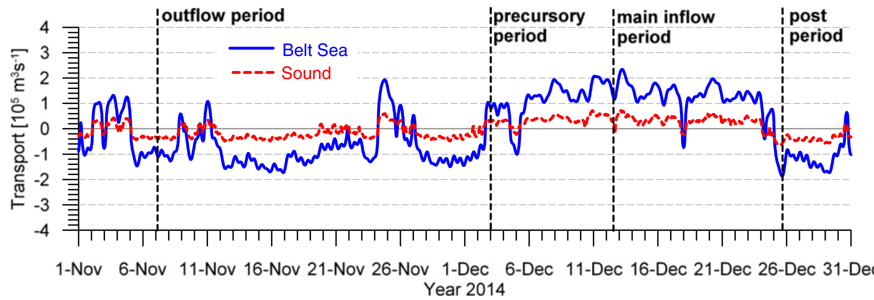

Fig. 9. Volume transport through the Belt Sea (solid blue line) and the sound (dashed red line) estimated from the sea level differences Hornbaek–Gedser and Viken–Klagshamn.

negative along channel velocities (outflow) throughout the water column. Only two short baroclinic inflow pulses were observed between 21st and 27th November. During the outflow period the salinity of about 8 indicated the outflow of brackish surface water. The baroclinic inflow pulses are also reflected in temporarily increased bottom salinity. The inflow phase at the Darss Sill started on 3rd December with positive along channel velocities of 0.25 to 0.50 ms^{-1}. Since the Belt Sea was previously flushed with low saline surface water, the salinity at the Darss Sill remains initially at low values, and increased slowly only during the precursory period. With 9 days delay to the Sound, the highly saline water was detected at the Darss Sill. On 13th December the salinity exceeded 17 in the entire water column. At this time no vertical salinity gradient was observed at the Darss Sill station (Fig. 7b). The arrival time of highly saline water at the Darss Sill determines the end of the precursory period. With 10 days duration the PCP of the MBI 2014 was rather short compared with the mean duration of 22 days given by Fischer and Matthäus (1996).

The current direction at the Darss Sill remained positive during the entire main inflow period that lasted until the 25th December. Mean current velocity was about 0.2 to 0.3 ms^{-1}. The bottom salinity increased during the entire MIP from 17 in the beginning to 22 on 25th December. At the Darss Sill the mean salinity was 18.56, averaged over the MIP. At the start of the post-period the surface salinity dropped drastically to about 8, the usual value for Baltic surface water. The bottom salinity remained at high values for a few days. This indicates an ongoing baroclinic leakage of highly saline bottom water from the Belt Sea into the Arkona Basin, temporary interrupted by a reflux of highly saline water from the Arkona Basin.

Fig. 7c demonstrates that the model can reproduce the observations very well. Also small events like the baroclinic pulses between 21st and 27th November 2014 are well represented. The modeled salinity at Darss Sill is in good agreement with the observed salinity profiles (Fig. 7c).

Fig. 8 depicts the oxygen concentrations measured at 7 and 19 m depths at the Darss Sill. Due to the exchange with the atmosphere the surface waters are well oxygenated during the months November and December. The oxygen saturation ranges between 95 and 100% in the surface layer. In the bottom layer the oxygen concentration was negatively correlated with the salinity until the start of the main inflow period. The higher saline waters of the baroclinic inflow pulses during the outflow phase and in the PCP were oxygen depleted. These waters were remainders of old saline bottom waters from the Belt Sea. The highly saline waters that enter the Baltic in the MIP were well oxygenated throughout the water column. Mean oxygen concentration and temperature of the inflowing saline water at the Darss Sill were 322 μmol l^{-1} and 6.29 °C, respectively.

For the estimation of total volume transports between the Baltic and the North Sea Eq. (3) was applied to the low pass filtered sea level measurements at the Landsort Norra. Since no actual runoff data were available, we considered the climatological mean freshwater surplus of 1.3 km^{3}d^{-1} for the calculation of volume transport. 242 km^3 of brackish surface water left the Baltic during the outflow period until 3rd December, causing a drop in mean sea level of 55 cm. In the inflow phase a total inflow of 323 km^3 was estimated. This was split into 161 km^3 for the PCP and 162 km^3 for the MIP.

A second estimate for the volume transports was derived from the sea level differences between the Kattegat and the Arkona Basin according to Eqs. (6) and (7) (Fig. 9). During the outflow period, the cumulated transports into the Belt Sea and the Sound amounted to −187 km^3 and −45 km^3, respectively. The sum of −232 km^3 is 10 km^3 less than the estimated from the sea level change at Landsort Norra. However, this is within the upper limit of the uncertainty of the method of 10%. During the inflow phase an inflow of 240 km^3 and 64 km^3 water was estimated for the Belt Sea and the Sound. Also during the inflow phase the sum of 304 km^3 water was slightly lower than the 323 km^3 estimated from the sea level change at Landsort Norra. The distribution of volume transports between the Belt Sea and the Sound was 8:1.9 during the outflow period, and 8:2.1 during the inflow phase. This is close to the relation of 8:2 given by Mattsson (1996).

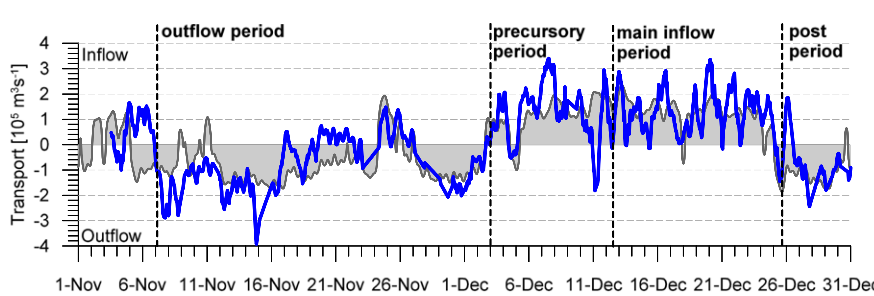

Fig. 10. Transports at the Darss Sill section calculated from the measurements of current velocity and salinity at the MARNET station Darss Sill (bold blue line) compared to Darss Sill transports based on sea level difference Hornbaek Gedser (thin gray line and shaded area).

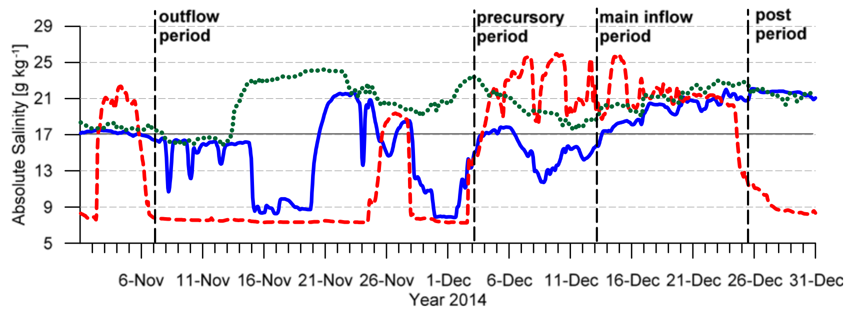

Fig. 11. Bottom salinity in the numerical model at MARNET station Darss Sill (solid blue line), Drogden Sill (dashed red line), and Gedser Rev (dotted green line).

The volume and salt transports at the Darss Sill were also estimated using the time series data of current and salinity, observed at the permanent MARNET station Darss Sill (see Fig. 7). During the outflow phase from 7th November to 3rd December the net outflow through the Belt Sea was calculated with -195 km^3. The inflow volume amounted to 110 km³ for the precursory period and 138 km^3 for the main inflow period. In the first days of the post-period an additional baroclinic inflow of 9 km^3 saline water was detected, which contributes to the total amount of the MBI inflow volume. The volume transports at the Darss Sill estimated from the sea level difference Hornbaek–Gedser and calculated from the Darss Sill current data are compared in Fig. 10. Generally, both time series show a similar behavior, and the same magnitude of transports. However, the transports derived from the direct current measurements depict a higher temporal variability. The differences are caused most probably by the local dynamics of the Darss Sill area and baroclinic processes, which are not recognized in the transport estimates based on sea level difference.

For the salt transport through the Sound only a rough estimate can be given, because no direct salinity measurements were available. The salinity observations at the MARNET station Arkona and also the CTD profiles from the western Arkona Basin indicated that the salinity of the inflowing water at the Sound was well above 23. This is confirmed by the modeled salinities. In contrast to the observational data, where the Practical Salinity is used as salinity scale, the model salinity is given as Absolute Salinity in units of g kg^{-1}. Fig. 11 indicates that the inflowing water via the Sound had salinities between 21 and 25. We used a salinity of 23 as mean value for the entire inflow period. Assuming, that the inflow water needs approximately 1 day to pass the Sound, 26 km^3 highly saline water entered the Baltic in the PCP. This corresponds to a salt transport of 0.60 Gt. During the main inflow period another 34 km^3 highly saline water added 0.78 Gt salt to the total salt transport of the MBI. The conversion between Practical Salinity and mass of salt (Absolute Salinity) was performed according to the international thermodynamic equation of seawater 2010 (IOC, SCOR and IAPSO, 2010).

Since the estimated transport through the Sound was based on several assumptions, we used the numerical model to get an independent estimate of the through flow. The modeled volume and salt flux through the Sound are close to the observations (compare Table 1). However, the GETM predicts slightly higher values. Nevertheless, the deviations are less than 10%.

The salt transport at the Darss Sill amounted to 2.60 Gt for the MIP and 0.17 Gt for first days of the post inflow period. Again, the model led values are 2.40 Gt close to the observational estimates. In addition, the transport values for the post-inflow are in good agreement. Table 1 summarizes the transport estimations from the different methods used for all phases of the MBI.

In order to compensate the lack of observational salinity and current meter data at the Drogden Sill an alternative approach was used to verify the calculation of the volume transport via the Sound. The CTD data, gathered between of 17th and 19th December on a cruise of RV "Elisabeth Mann Borgese", supplied a distribution of the different inflow

Table 1
Summary of transport calculations. Netto volumes (V) in km^3 transported during the particular inflow periods. Numbers in brackets depict the fraction of inflow volumes that carry highly saline water into the Baltic. The last two rows (bold) summarize the volumes estimated from observations and numerical model.

Period	Outflow period 07.11.2014–03.12.2014	Precursory period 03.12. 2014–13.12.2014	Main inflow period 13.12.2014–25.12.2014	Total inflow phase 03.12.2014–25.12.2014	Post inflow 25.12.2014–31.12.2014
V_{total} [km^3] Sea level change Landsort	−242	161	162	323	−111
V_{Sound} [km^3] Sea level difference Viken–Klagshamn	−45	30 (26) 0.60 Gt salt	34 (34) 0.78 Gt salt	64 (60) 1.38 Gt salt	−22
V_{Sound} [km^3] Numerical model	−67.5	37.5 0.59 Gt salt	38.9 0.85 Gt salt	76.4 1.44 Gt salt	−33.4
$V_{Darss\ Sill}$ [km^3] Sea level difference Hornbaek–Gedser	−187	103	137	240	−59
$V_{Darss\ Sill}$ [km^3] Current and salinity measurements at MARNET Darss Sill	−195	110	138 (138) 2.60 Gt salt	248 (138) 2.60 Gt salt	−43 (9) 0.17 Gt salt
$V_{Darss\ Sill}$ [km^3] Numerical model	−145.8	70.6 0.16 Gt salt	134.4 2.24 Gt salt	205.0 2.40 Gt salt	−63.5 0.11 Gt salt
V_{total} [km^3] $V_{Darss\ Sill} + V_{Sound}$ Observations	**−235**	**140** **(26)** **0.60 Gt salt**	**172** **(172)** **3.38 Gt salt**	**312** **(198)** **3.98 Gt salt**	**−65** **(9)** **0.17 Gt salt**
V_{total} [km^3] $V_{Darss\ Sill} + V_{Sound}$ Numerical model	**−213.3**	**108.1** **0.75 Gt salt**	**173.3** **3.09 Gt salt**	**281.4** **3.84 Gt salt**	**−97** **0.11 Gt salt**

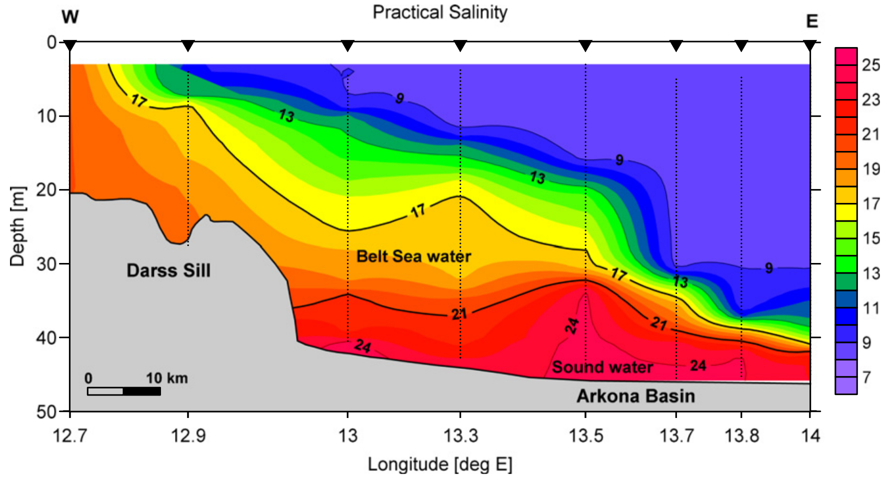

Fig. 12. Vertical salinity distribution along a transect from the Darss Sill to the center of Arkona Basin (17th to 19th December 2014). Positions of CTD stations and transect are depicted in Fig. 1.

water masses in the western Arkona Basin. Fig. 12 shows the vertical salinity distribution along a transect from the Darss Sill to the center of Arkona Basin. The inflowing saline water masses from the Belt Sea and the Sound depict different properties. According to the time series data from the MARNET stations Darss Sill and Arkona Basin the salinity of Belt Sea water ranged between 17 and 21, whereas the salinity of the Sound water was higher than 21. Thus, the isohalines with salinity of 17 and 21 were used to identify the both inflow water bodies. In the Arkona Basin the Sound water showed a maximum salinity of 26 and a mean value of 22.8. Its mean temperature and oxygen content were of 8.2 °C and 275 μmol l^{-1}. The water that entered the Arkona Basin via the Belt Sea had a lower mean salinity of 18.9, a temperature of 7.3 °C, and an oxygen concentration of 307 μmol l^{-1}. Beside these parameters the Sound water depicted a higher turbidity compared to the Belt Sea water (not shown). Due to its lower density the Belt Sea water is sandwiched between the old Arkona Basin water and the highly saline Sound water.

For the Arkona Basin section of the CTD transect, with water depth greater than 30 m, the fractions of the particular water masses were estimated. In the period of 17th–19th December 62% of the volume consisted of less saline surface water and uplifted former bottom water. 18.8% were covered by highly saline water from the Belt Sea and 19.2% by water that originated from the Sound. A linear extrapolation to the total volume of the Arkona Basin of 225 km³ supplied a very raw, but independent estimate of the inflow volumes. The derived volumes of Belt Sea water and Sound water are 42 km³ and 43 km³, respectively. The calculated transport of highly saline water via the Darss Sill amounted to 54 km^3 till 17th December. This increased until the 19th December to about 73 km^3. The cumulated inflow volume of highly saline Sound water was 40 km^3 and 44 km^3 on the 17th and 19th December, respectively. This compares with the range of uncertainties with the volume estimates derived from the CTD data.

Measurements of sea surface salinity (SSS) from the MARNET stations Darss Sill and Arkona Basin were combined with data gathered on board of the ferry “Finnmaid” and the RV “Elisabeth Mann-Borgese” to investigate the temporal behavior of the surface salinity front in the Darss Sill area (Fig. 13). The SSS front depicted by the salinity 17 isohaline reached the MARNET station Darss Sill on 13th December with the start of the MIP. The MARNET station Darss Sill was the eastern most position of the salinity 17 isohaline. Further to the east the highly saline water descents underneath the surface waters of the Arkona Basin. On 21st December the SSS front moved westward to 12.5°E between the MARNET station and the Kadet Furrow, and remained at this position until the end of the MIP.

4. Discussion

The main aims of the presented study are the investigation of the development and the dynamics of the exceptional Christmas MBI 2014, its classification and the estimation of its possible impact on the Baltic Sea ecosystem. For classification in principle two scales are available: the intensity index Q_{FMS87} developed by Franck et al. (1987) and the new intensity scale Q_{FM96} by Fischer and Matthäus (1996). The latter one is the more appropriate scale, since it is based on the total salt amount

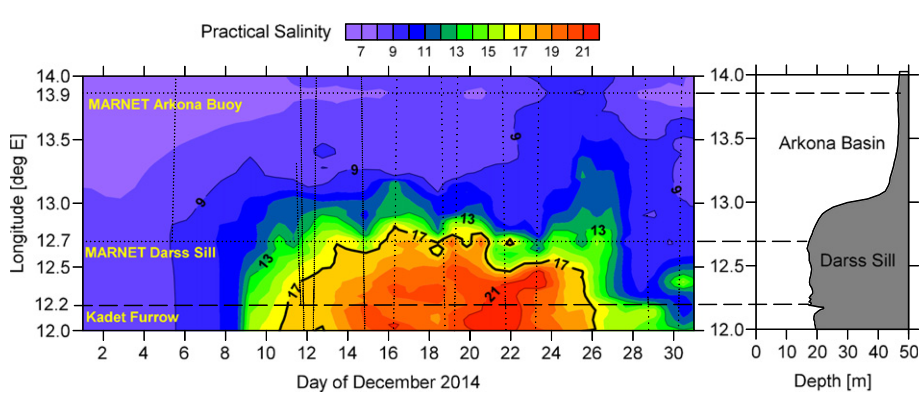

Fig. 13. Hovmöllerplot of surface salinity (left) and depth profile (right) along a transect from the Kadet Furrow (Gedser Rev) to the central Arkona Basin. Data from “Finnmaid” ferry and MARNET stations Darss Sill and Arkona buoy (dotted lines). The dashed line indicates the historical position of light vessel Gedser Rev.

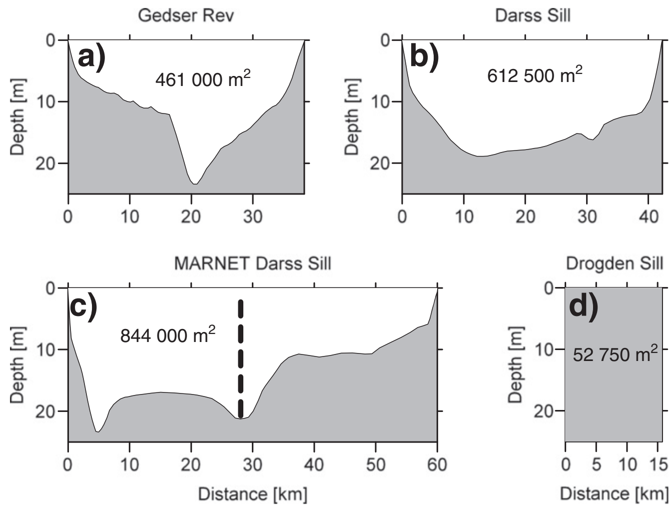

Fig. 14. Geometry and cross section area of across channel sections at Gedser Rev (a), Darss Sill (b). MARNET station Darss Sill (c) and Drogden Sill (d). The dashed line in panel (c) depicts the position of the MARNET station Darss Sill.

transported into the Baltic Sea. However, in order to compare our results to earlier studies we also calculated the intensity index Q_{FMS87}. Using this intensity scale the MBI 2014 has an intensity index of $Q_{FMS87} = 26.1$ ($k = 12.46$ d, $S = 18.56$), based on the observations at the MARNET station Darss Sill. For comparison, the previous MBI in 2003 had an intensity index of 12.1 on the same scale (Feistel et al., 2003b).

It should be recognized that the application of the FMS87 index onto the actual Darss Sill data might be inconsistent. The MARNET Station Darss Sill is located 46.9 km eastward of the position of the light vessel Gedser Rev and 21 km eastward, or downstream of the topographic Darss Sill. Assuming an upper limit of mean current velocity of 0.4 ms^{-1} the inflowing water needs approximately 32 h from Gedser Rev to MARNET station Darss Sill. This will lead to an underestimation of inflow intensity FMS87 for events that are deduced from data of the MARNET Darss Sill station. The temporal difference of the presence of SSS greater 17 between the Kadet Furrow station and the MARNET station Darss Sill is illustrated in Fig. 13. To improve the estimation of inflow intensity FMS87 one can apply a correction of k for the distance between Gedser Rev and MARNET station Darss Sill using an offset $k_0 = 2{*}32$ h $= 2.6$ days. Using this approach, the Q_{FMS87} has the more realistic value of 31.3 for the MBI 2014.

There is also a significant difference in topography between the cross sections at Gedser Rev, Darss Sill and MARNET station Darss Sill (compare Fig. 14). The Gedser Rev section has the minimal cross section area of 0.461 km^2. The Darss Sill section depicts the shallowest bottom depth of 18 m. The cross section area at the MARNET station Darss Sill is approximately double as large (0.844 km^2) as the cross section area at the Gedser Rev, and the maximum bottom depth is 23 m. Thus, the section at the MARNET station Darss Sill is often not completely covered by inflowing saline waters passing the Gedser Rev section.

The MARNET station Darss Sill is closely located to the western rim of the Arkona Basin. The inflowing saline water starts to subduct in the vicinity of the station. Therefore the salinity front fluctuates around this position during the inflow phase. Especially in the second half of the MIP the surface layer at the MARNET station Darss Sill is covered occasionally by low saline surface water, whereas the inflow continues at deeper layers (compare Fig. 7). In this phase the increasing salinity of inflowing waters forces a faster subduction. Due to the shallow layer of low saline surface waters the stratification coefficient G exceeds the MBI limit of 0.2.

To identify an inflow as MBI, Franck et al. (1987), and also Fischer and Matthäus (1996) used the criteria, that for at least five consecutive days the bottom salinity must be equal to or exceeding 17, and the stratification coefficient G must be equal to or below 0.2. Minor MBIs which fulfill these criteria at the Gedser Rev, may not do this at the MARNET station Darss Sill. Due to the shift of the continuous observations from the Gedser Rev to the MARNET station Darss Sill in the 1980s, most probably some weak to moderate MBIs was not identified as a MBI, since they did not fulfill the MBI criteria at the MARNET station Darss Sill. This view is supported by the complete lack of weak MBIs since 1983, which should be the MBI class with the highest frequency. However, the necessary revision of the MBI statistics exceeds the frame of the present study and will be done in a future work.

The impact of the measuring position can be illustrated for the MBI 2014 by using the modeled salinity. The application of the MBI criteria to the positions Gedser Rev and MARNET station Darss Sill resulted in a huge difference in the FMS87 index. At Gedser Rev the MBI criteria is fulfilled for 19.3 days. Regarding the mean salinity of 20.5, the FMS87 index of the MBI 2014 is 53.6 which is a very strong inflow at this scale (>45). In contrast, the duration of 11.4 days and the mean salinity of 19.4 at the MARNET station Darss Sill revealed an inflow intensity of 30.1 on the FMS87 scale, pointing on a medium to strong inflow. Fig. 15 depicts the stratification coefficient G and the periods when the MBI criteria are fulfilled in the numerical model at the particular stations. It shows an additional minor MBI in the first week of December which is not seen at the MARNET station Darss Sill.

The use of salt transports for MBI classification, introduced by Fischer and Matthäus (1996), will overcome the problem of measuring location. Between the 13th of December and the end of the main inflow phase on 25th December the cumulated transport into the Baltic via the Darss Sill amounts to 138 km^3 saline water with 2.6 Gt salt (based on Darss Sill current and salinity measurements). It should be also mentioned that during the post-inflow period a substantial amount of salt

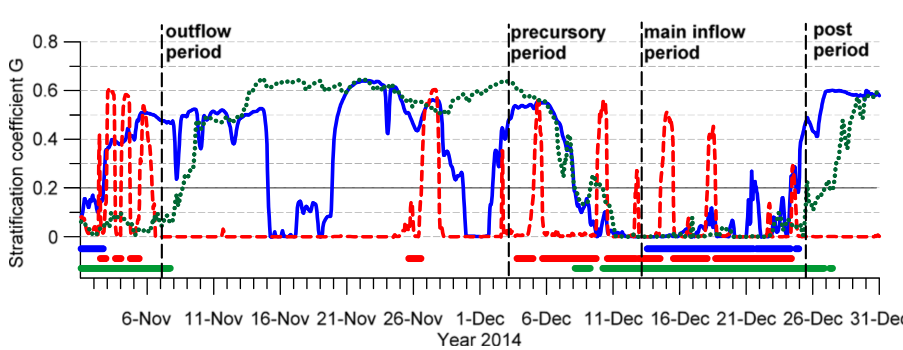

Fig. 15. Stratification coefficient G in the numerical model at MARNET station Darss Sill (solid blue line), Drogden Sill (dashed red line), and Gedser Rev (dotted green line). The periods, when stratification coefficient G was lower than 0.2 and bottom salinity was higher than 17 are indicated by the bold colored lines at the bottom of the graph (top — Darss Sill, middle — Drogden Sill, bottom — Gedser Rev).

Table 2
Comparison of the five strongest major Baltic inflows since 1880 (Fischer and Matthäus, 1996) with the actual inflow in December 2014 (bold) and the previous MBI in 2003 (last row).

Rank	MBI	Salt [Gt]	Volume total [km^3]	Salinity Belt	Volume Belt [km^3]	Salinity Sound	Volume Sound [km^3]
1	November/December 1951	5.17	225	22.5	172	24.7	53
2	December 1921/January 1922	5.12	258	19.2	202	22.2	56
3	**December 2014**	**3.98**	**198**	**18.56**	**138**	**23.0**	**60**
4	November/December 1913	3.80	174	21.0	123	23.6	51
5	January 1993	3.40	159	18.7	93	25.2	66
6	November/December 1897	3.35	177	18.5	147	21.3	30
26	January 2003	2.03	97	18.3	65	26.0	32

(0.17 Gt in the observations, 0.11 Gt in the model simulation) passed the MARNET section Darss Sill eastward. The salt transport via the Sound was estimated with 1.38 Gt. The transports were verified by four independent methods: sea level change at Landsort Norra, sea level differences in the Belt Sea and the Sound, direct measurements of salinity and currents at the MARNET station Darss Sill, and numerical modeling of the inflow. Within their uncertainties all methods reveal similar volume and salt transports. Although the flow contributions between the Sound and Darss Sill in the observations and the numerical model differ slightly note that the deviations in the total transports are less than 10%.

Using the intensity index FM96, the Christmas MBI 2014 was classified as a very strong inflow ($Q_{FM96} = 39.8$). In the record of historical MBIs (Table 2), the 2014 event is the third strongest since 1880 and the strongest since 1951. Only the MBI in 1993 was of comparable size during the last 60 years (Fig. 16).

The MBI 2014 was characterized by a short duration of the precursory period of 10 days. This was only half of the mean PCP duration determined by Fischer and Matthäus (1996) with 22 days. The short PCP was caused by the very rapid and strait rising of the average Baltic Sea sea level with a mean rate of about 4.27 cm d^{-1}, corresponding to an inflow of about 15 km^{3}d^{-1}. Thus, the volume of 140 km^3 water which was entering the Baltic during the PCP (Matthäus and Franck, 1992) was reached rapidly until the 13th of December. The short PCP reduced the impact of freshwater runoff on the inflow. Assuming a climatological mean freshwater runoff of 1.3 km^{3}d^{-1}, the freshwater surplus was about 13 km^3 during the PCP of the 2014 MBI. This was 15 km^3 less, compared to the mean PCP duration, and increased the capacity of the Baltic Sea for inflowing saline water by about 10%.

This paper describes the evolution of the MBI until the end of 2014, thus covering only the penetration till the Arkona Basin. The MBI 2014 has the potential for a crucial change of the environment conditions in the deep Baltic basins. Using the mean oxygen concentration of inflowing saline water of 322 µmol l^{-1} (compare Fig. 8) and the total saline water inflow volume of 198 km^3 the total amount of oxygen transported into the Baltic was estimated with 2.04 10^6 t. This was three times more than the 6.5 10^5 t oxygen equivalent of hydrogen sulfide found in the Gotland Basin in November 2014 (Schmidt, 2014). Most probably the MBI will finish the 10 year stagnation period in the central Baltic Sea.

However, the biogeochemical effects in the deeper basins of the Baltic Proper cannot be evaluated yet exactly. But experiences from earlier MBIs can give a hint to the future development in the central Baltic. We selected the MBI from January 1993 being the fifth strongest event on record (Table 2).

The water renewal during the first half of the 1990s and the subsequent development of a new stagnation period can be recognized most distinctly by the variations of nutrient concentrations in the eastern Gotland Basin. At the end of the 16 year stagnation period in 1992 hydrogen sulfide concentrations, expressed as negative oxygen equivalents, up to −8 ml l^{-1}, in the near-bottom layer up to −10 ml l^{-1}, were measured with a high degree of variability. The nutrient situation is characterized by the absence of nitrate and nitrite and a considerable enrichment of ammonium up to 40 µmol l^{-1} and phosphate concentrations of 6–7 µmol l^{-1} (Nehring et al., 1995). In 1993, the nutrient distribution reacted distinctly to the changes in the redox regime in the eastern Gotland Basin. Ammonium is decreasing strongly and was not detectable in June and August 1993. Nitrate concentrations increased up to 6 µmol l^{-1} and the amount of phosphate was reduced to 3 µmol l^{-1} (Nausch and Nehring, 1994). But, the layer below 200 m depth became anoxic again in November 1993. Only further weak inflows at the end of 1993/beginning of 1994 resulted in a longer improvement of the oxic situation in the Gotland Deep due to their fast penetration into the eastern Gotland Basin. As a result, quite low phosphate (2 µmol l^{-1}) and ammonium concentrations (near zero) but highest nitrate concentrations (11–12 µmol l^{-1}) were observed in 1995 before the new stagnation had started. From the mid-1998 onwards, when permanent anoxic conditions prevailed, nitrate was not detectable and phosphate and ammonium concentrations were increasing.

Due to vertical mixing processes (Reissmann et al., 2009) nutrients can be transported upwards and when reaching the euphotic surface

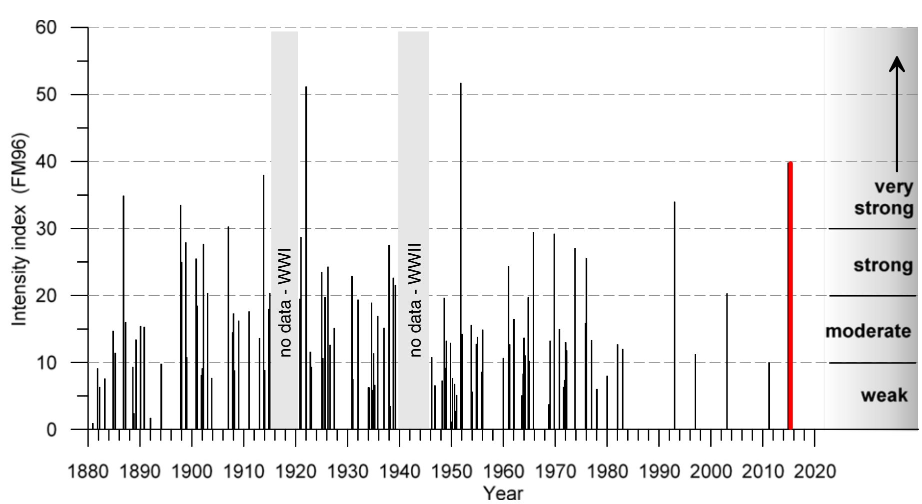

Fig. 16. Intensity index FM96 (Eq. (2)) of MBIs for the period 1880 to 2014 (extended after Matthäus et al., 2008; data from Feistel et al., 2008).

layer they may determine to a large extent the intensity of primary production. Thus, a lower amount of phosphate enriched in the deep water could result in lower winter concentrations in the surface layer with consequences for the productivity during spring and summer. However, these vertical transport mechanisms are by far not sufficiently understood in time and quantity. It seems to be that there is a time delay of several years between changes in the deep and reactions in the surface as passive tracers like salinity suggest (Nausch et al., 2014).

5. Summary and conclusion

After a stagnation period that lasted for 10 years, just before Christmas 2014 a very strong major Baltic inflow brought a large amount of saline water into the Baltic Sea. Field observations from various sources and numerical simulation were used to investigate the evolution of the inflow in the Danish Straits and the western Baltic Sea. The inflow was preceded by calm wind conditions and high air pressure over central Europe in autumn 2014. Long lasting easterly winds in November 2014 caused a strong outflow of Baltic surface water and a drop of the mean sea level in the Baltic Sea to 47 cm below zero. The change to long lasting westerly winds in the beginning of December forced the inflow of saline water from the Kattegat through the Danish Straits into the Arkona Basin. The westerly winds and the saline inflow persisted until Christmas 2014. The major aims of this study were the classification of the MBI intensity and the estimation of volume and salt transports.

The main results of the study are:

- The Christmas MBI 2014 was the third largest saline inflow event ever observed since the beginning of Matthäus' retroperspective analysis in 1880. Based on the intensity scale FM96 the MBI has an intensity index of 39.8.
- The total inflow volume was about 320 km^3, with 198 km^3 of highly saline water. Between the 3rd and 25th December 2014 the MBI carried approximately 4 Gt salt into the Baltic Sea. The inflow volume of highly saline water and the salt transport split between the Belt Sea and the Sound to 138 km^3 with 2.60 Gt salt and 60 km^3 with 1.38 Gt salt, respectively.
- The lack of systematic and freely available observational data of salinity and current direction in the Sound is the major reason for some uncertainty of the quantitative estimations of salt transport.
- The application of the original MBI criteria given by Franck et al. (1987) and Fischer and Matthäus (1996) to the data from the MARNET station Darss Sill will result in a systematic underestimation of the inflow intensity. Thus, most probably a number of weak and medium size MBIs were not recognized in the statistical analyses since the 1990s.
- The results of the high spatial resolution, numerical modeling with GETM are in good agreement with the observations of the inflow. The model derived volume and salt transports are very close to the estimates, based on observations. The deviations are small and can be explained by the uncertainties of the applied methods.
- The MBI 2014 has the potential to stop the stagnation period, lasting since 2003, and to turn the entire deep water of the Baltic into oxic conditions.

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