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Baltic Sea freshwater content

Urmas Raudsepp, Ilja Maljutenko, Amirhossein Barzandeh, Rivo Uiboupin, Priidik Lagemaa

Department of Marine Systems, Tallinn University of Technology, Tallinn, 12618, Estonia

Correspondence to: Urmas Raudsepp (urmas.raudsepp@taltech.ee)

Abstract.

The Baltic Sea is a brackish shallow sea, the state of which is determined by the mixing of the freshwater from net precipitation and runoff with the salty water from the North Sea inflows. The climatological freshwater content is calculated from the Copernicus regional reanalysis. The seasonal freshwater content reflects the specific hydrophysical conditions of each sub-basin, with northern basins being influenced by the seasonal runoff and ice formation the southern basins are more responsive to subsurface salinity changes. The total freshwater content in the Baltic Sea shows steady decrease over the past two decades with a linear trend of 23.9 km^3 per year, however the trend has significant spatial variability. In the northern Baltic the freshwater content is influenced by the increase of runoff and decrease of ice formation, which results in positive freshwater content tendencies, while in the southern parts the salty water supply has reduced the freshwater content.

Short Summary. The freshwater content in the Baltic Sea has wide sub-regional variability characterised by the local climate dynamics. The total freshwater content trend is negative due to the recent increased inflows of salt water, but there are also regions where the increase in runoff and decrease in ice content have led to an increase of the freshwater content.

1 Introduction

Climate warming has resulted in the intensification of the global hydrological cycle, but not necessarily on the regional scale (Pratap and Markonis, 2022). The increase of net precipitation over land and sea areas, decrease of the ice cover and increase of river runoff are the main components of the global hydrological cycle that increase freshwater content (FWC) in the ocean (Boyer et al., 2007) and decrease ocean salinity. All the components can be directly estimated, but might have significant uncertainties. Instead, the ocean salinity change can be used as a marker of the water cycle change (Durack et al., 2012).

In the case of an open part of the ocean, e.g. a regional sea, using salinity as proxy for the FWC includes an additional blurring aspect, which is water transport through the open boundaries between the basin under consideration and surrounding area. The impact of water exchange on the changes of the FWC is significant if not dominant. In that case, changes of the FWC may not represent the actual changes of freshwater input from the abovementioned sources.

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The Baltic Sea is one of the marginal seas where water salinity and FWC are strongly influenced by the water exchange with the North Sea. The Major Baltic Inflows (MBIs) are the most voluminous event-type sources of saline water to the Baltic Sea (Mohrholz, 2018). Direct total input of freshwater to the Baltic Sea consists of river runoff and net precipitation. Thus, the long-term salinity of the Baltic Sea is determined by saline water inflows from the North Sea and its dilution with freshwater originating from numerous rivers across the Baltic coast and from the net precipitation (Lehmann et al., 2022). A specific feature of the Baltic Sea is the large difference in sea surface salinity between about 20 g/kg in Kattegat and 2 g/kg in the Bothnian Bay (Leppäranta and Myrberg, 2009).

A common approach is to use salinity to describe the energy and water cycles in the Baltic Sea (Lehmann et al., 2022 and references therein). In this study, instead of using spatially mean salinity of the Baltic Sea, we suggest the concept of the FWC (Boyer et al., 2007) for the description of the physical state of the Baltic Sea. Previously, a concept of the FWC has been used to estimate the freshwater budget of the Baltic Sea (Winsor et al., 2001) and for the geographical spreading of spring-time river runoff (Eilola and Stigebrandt, 1998).

The aim of this study is to analyse the changes of the Baltic Sea FWC during the period of 1993–2021. The MBI in 1993 ended the stagnation period with no MBIs that lasted for about 10 years (1983–1993). During the stagnation period the salinity was below average, the stratification weakened and hypoxic area decreased (Lehmann et al., 2022). The period of 1993–2021 includes the third in volume MBI in 2014 (Mohrholz et al., 2015) and a number of the other barotropic large volume inflows (Mohrholz, 2018). We focus on the changes of the FWC in the whole Baltic Sea, but also in its sub-basins. We investigate the trends in the FWC and observe its seasonal changes. A qualitative explanation of the physical processes behind the dynamics of the FWC is provided.

2 Data and methods

The BALMFC CMEMS reanalysis product (data ref. 1, Table 1) is calculated using the Nemo-Nordic 1.0 ocean model (Hordoir et al., 2019). The horizontal resolution of the model is approximately 2 nautical miles and there are 56 vertical levels. Vertical resolution varies from 3 m at the surface up to 10 m below the 100 m depth. The model without data assimilation has been thoroughly validated (Hordoir et al., 2019,). The Copernicus model system uses Localised Singular Evolutive Interpolated Kalman filter data assimilation method (Liu and Fu, 2018).

The FWC is calculated according to Boyer et al. (2007) as following

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$$FWC = \frac{\rho(Sref, Tref, p)}{\rho(0, Tref, p)} \frac{\Delta S}{Sref + \Delta s}, \qquad [1]$$

where ΔS is a salinity anomaly from reference salinity Sref (S (x, y, z, t) - Sref (x, y, z)) and x,y,z,t are indexes in zonal, meridional, vertical and temporal dimensions respectively. The density (ρ) is calculated according to TEOS10. The key issue is how the reference salinity is defined. The climatological range of salinity in the Baltic Sea varies from the fresh conditions in the northern and easter parts up to the oceanic conditions in Kattegat. Therefore we follow the Boyer et al. (2007) formulation and calculate the climatological FWC from the three dimensional temperature (Tref) and salinity (Sref) fields averaged over the period of 1993–2020.

The total volume of freshwater which is needed to add/extracted to bring the ocean state to the level of reference salinity is a integral over different spatial dimensions

For total volume:

$FWC(t) = \iiint_V FWC(x,y,z,t) \; dxdydz$ [$m^3 \, m^{-3}$],

vertical distribution of freshwater

$FWC(z,t) = \iint_A FWC(x,y,z,t) \; dxdy$ [$m^2 \, m^{-3}$],

and spatial distribution of freshwater

$FWC(x,y,t) = \int_D FWC(x,y,z,t) \; dz$ [$m \, m^{-3}$].

Where the V and A correspond to the volume and area of the Baltic Sea or its sub-region which are shown on Fig 1. The D corresponds to depth from surface to bottom.

Then the linear trend of ice volume (Vi) over 1993–2020 (28 years) is calculated from the same BALMFC CMEMS reanalysis product (data ref 1, Table 1) based on LIM3 model configuration (Pemberton et al., 2018). The ice volume is calculated for each model grid cell(x,y) using the total ice thickness (Hi) and the ice concentration (Ci) as below:

$Vi(x,y,t) = Hi(x,y,t) * Ci(x,y,t) * dA(x,y)$,

where dA is the area of each grid-cell.

The hourly precipitation and evaporation data has been extracted from the ERA5 reanalysis (data ref 2, Table 1) from the period of 1993-2020. The net precipitation was calculated by subtracting evaporation from precipitation. Further, the net precipitation was interpolated on a 2 nautical mile grid (ocean model) and total net precipitation was estimated for the wet grid-cells of each sub-basin shown in Fig. 1.

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The total runoff from the Baltic Sea rivers was estimated from the river discharge database (data ref 2, Table 1) of the Baltic Model Intercomparison Project (Väli et al., 2019). The runoff from each river was accumulated to the corresponding sub-basin runoff (Fig. 1.) and the accumulated anomaly of the annual runoff was calculated for the reference period of 1993-2018.

3 Results and Discussion

The FWC of the Baltic Sea has a negative trend of -23.9 ± 0.7 km^3/y ($p < 10^{-3}$) superimposed by irregular multi-year variations (Fig. 2a). The trend is variable over the whole Baltic Sea. It changes sign from positive in the northern sub-basins to neutral in the eastern sub-basins and to negative in the central and southern sub-basins (Fig. 2). The decrease of the FWC in the southern Baltic Proper contributes the most to the overall decreasing trend of the FWC in the Baltic Sea. Detailed spatial distribution of the trends shows the opposite temporal regimes of the FWC in the Bothnian Bay and in the Baltic Proper with Bothnian Sea as the transition area (Fig. 3a). Although there is no trend in the Gulf of Finland as a whole (Fig. 2), the eastern part has a small negative trend while the western part shows a small positive trend. The shallow Gulf of Riga has a negligible trend. The trends vanish in the southwestern Baltic Sea and in the Kattegat area (Fig. 3a).

The range of variation of the FWC differs about an order of magnitude between the sub-basins (Fig. 2) due to different water volumes of the sub-basins. When normalized to the corresponding volume of the sub-basin, we can see that the variations of the FWC affect 10% of the volume of the Baltic Sea (Fig. 2a). The variability of normalised FWC is highest in the Kattegat, relatively high in the Bothnian Bay and the Gulf of Finland and lowest in the Bothnian Sea (figure 2, figure 3b).

The correlation coefficients calculated pairwise between detrended FWC time series (Table 1) show a high positive value between the southern and northern Baltic proper (R=0.8) and between the Bothnian Bay and Bothnian Sea (R=0.6), while the correlation between the Bothnian Bay and southern and northern Baltic proper is negative (R=-0.6).

Time-depth variations of the FWC in each sub-basin are shown in Fig. 4. In the whole Baltic Sea, the FWC is the most variable in the halocline layer and beneath (Fig. 4a). Vertical distribution of the trends shows the absence of the trend in the upper layer of 50-m, but strong negative trend within and below the halocline. Thus, the decrease of the FWC in the whole Baltic Sea is mostly caused by the drop of the FWC below the upper mixed layer. The variability as well as negative trends are strongest in the southern and the northern Baltic Proper (Fig. 4e,c). The decrease of the FWC is explained by the saline water transport from the North Sea to the Baltic Sea by the Major Baltic Inflows (Mohrholz, 2018), large barotropic inflows (Lehmann et al., 2017) and smaller inflows of barotropic origin (Lehmann et al., 2022). The negative trend extends in the deeper layer (deeper than 50 m) of the Gulf of Finland and in the Bothnian Sea (Fig. 4f,d). Deep layer water in the Gulf of Finland originates from the sub-halocline layer (110−120 m) of the central Baltic Proper (Liblik et al., 2018). Marginal

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decreasing tendency of the FWC in the Bothnian Sea is explained by the small fraction of the more saline deep water flowing in over the sills between the northern Baltic Proper and the Bothnian Sea (Lehmann et al., 2022). In the upper layer of 50 m, the variability of the FWC is the highest in the Bothnian Bay. There is a strong positive trend that extends down to the bottom of the sub-basin (Fig. 4b). The positive trend of FWC in the upper layer is seen in the Bothnian Sea and in the Gulf of Finland. In the Gulf of Riga the variability is moderate and the trends are negligible. We would like to note that in the northern Baltic Proper the trend is absent in the upper layer of 30-m, but turns negative in the surface layer of the southern Baltic Proper.

To explain the trend in the upper layer we have calculated freshwater supply by the rivers and by net precipitation. Additionally, we consider the decrease of the ice volume as a potential freshwater source. In the Bothnian Bay, a large positive trend in FWC could be qualitatively explained by the negative trend of ice volume (Fig. 3c). The negative trend of the ice volume is also seen in the eastern part of the Gulf of Finland (Fig. 3c), where FWC showed a positive tendency (Fig. 3a). Thus, warming of the winters (Kotta et al., 2018) could cause a decrease of the ice volume and increase of the FWC in the northern and far eastern parts of the Baltic Sea. In support of this hypothesis Garric et al. (2018) have shown that decrease in the ice volume in the Arctic is correlated with the increase of the FWC. A tendency of increasing river runoff contributes to the FWC in the Bothnian Bay and in the Gulf of Finland (Fig. 5f). Net precipitation has increased over the Bay of Bothnia and over the Bothnian sea (Fig. 6b,d). In the Baltic Sea as a whole there is no trend in the net precipitation (Fig. 6a) nor in river runoff (Fig. 5a).

The seasonal dynamics of FWC further emphasise the decoupling of the northern and southern sub-basins of the Baltic Sea (Fig. 7). The Gulf of Bothnia has low FWC in winter and early spring and high in summer and autumn. The seasonal course is more pronounced in the Bothnian Bay than in the Bothnian Sea. In the Gulf of Bothnia, decrease of FWC in winter could be associated with the freezing of seawater. The minimum FWC is reached in March and April in the Bothnian Bay while the lowest FWC in the Bothnian Sea is in February and March. These months coincide with the months of maximum sea ice extent in these basins (Raudsepp et al., 2020). During the ice melting period from April to June FWC starts to increase.

In the southern Baltic proper, FWC is low in winter and high in summer, while in the Gulf of Finland the situation is the opposite. In the southern Baltic proper, large volume inflows of saline water take place in winter (Raudsepp et al., 2018; Lehmann and Post, 2015; Mohrholz, 2018), which reduces the FWC. In the Gulf of Finland the seasonal changes of FWC are determined by intensive estuarine circulation in summer and the associated salt wedge dynamics (Maljutenko and Raudsepp, 2019). In winter, the salt wedge withdraws from the interior of the gulf, the mean salinity decreases and FWC increases. The formation and melting of the sea ice has a smaller effect on the FWC than in the Bothnian Bay. The seasonal course of FWC is almost absent in the northern Baltic Proper where the influence from adjacent sub-basins, the southern Baltic Proper and the Gulf of Finland, which have opposite FWC seasonality, could compensate each other. In the Gulf of

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Riga, FWC is at its maximum in spring and then decreases monotonically until the winter. In the Gulf of Riga, the seasonal course of the FWC is explained by the high river runoff in spring with a climatological monthly mean freshwater flux of 3400 m^3/s in April (Raudsepp, 2001).

Surprisingly, the seasonal course of the FWC in the Kattegat is similar to the seasonal course of the FWC in the Gulf of Riga. Dynamically these two areas cannot be interlinked due to their geographical separation. Increase of FWC in the Kattegat in spring is the result of the outflow of low salinity water from the Baltic Sea manifested by low sea level in the Baltic Sea (Raudsepp et al., 1999). The seasonal course of the FWC of the entire Baltic Sea is shaped mainly by the seasonal course of the FWC in the southern Baltic Proper, but also has a contribution from the freshwater supply from the rivers in spring.

The long-term tendencies show similar propagation with the natural estuarine exchange, where salty inflow in the sub-surface layer is gradually mixed in the upper layer which exhibits outflow towards the ocean. The elevated salinity inflows to the Baltic Sea reduce the FWC compared to the climatology in the deep layers of the southern Baltic Sea - this can be manifested from the negative trends below the permanent halocline in the southern and northern Baltic Proper (Fig. 4c,e). While salt inflows propagate to downstream basins (northern Baltic Proper, Gulf of Finland) and from the gradual mixing the surface layers should also exhibit negative tendencies, in case of the assumption that the freshwater inflow to the system does not change. These tendencies are either weak or non-existent in the Baltic Proper (Fig 4), which suggest that the increased freshwater runoff and positive FWC tendencies in the northern sub-basins of the Baltic Sea have compensated corresponding trends of the FWC.

The definition of the FWC to the reference salinity determines the amount of freshwater necessary to bring the solution to the reference salinity (Boyer et al., 2007) therefore it characterises volumetric influence of freshwater toward the reference state. As such the FWC has a nonlinear relationship toward the change of the state (salinity) compared to its reference (climatology). In the Baltic Sea, where salinity climatology shows large gradients between sub-basins, such a relationship emphasises salinity changes in the southern (saltier) and northern (fresher) sub-basins differently.

Thus, the FWC could be a complementary proxy to characterise salinity stress to freshwater species adapting with the brackish water of the Baltic Sea (Vuorinen et al., 2015). And wise verse - the decrease of FWC which has nonlinear relationship to the unit-changes of salinity could be an indicator for the alien species, which favour higher salinity conditions.

Quantitative estimation of the FWC budgets and their relationships toward the cumulative freshwater runoff and salty water inflows are out of the scope of the current study

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Conclusions

The climatological FWC of the Baltic Sea show substantial variability both in time and different sub-regions. The northern sub-basins of the Baltic Sea show positive tendencies of FWC while in the Baltic Proper mostly negative tendencies are witnessed. The total FWC of the Baltic Sea has decreased steadily with the rate of 23.9 km^3/y. This decrease is caused by the increase of saline water transport from the North Sea to the Baltic Sea. Seasonal course of FWC in different sub-basins highlights the local dynamics and explains the FWC dynamics in relation to the local sources of freshwater. The relationship of the FWC to the salinity changes is nonlinear toward the corresponding reference state, therefore any of the extrapolations to new states i.e "ocean" or "lake" should be avoided.

Climate warming effect is manifested in reduced ice formation and increased net precipitation in the north-eastern sub-basins. This has led to the increase in FWC in the Bothnian Bay and eastern Gulf of Finland due to reduced retention of freshwater in ice and increase in runoff/net precipitation of freshwater. These FWC tendencies propagate towards the southern sub-basins according to the estuarine exchanges which results in compensation of FWC trends in surface layers there.

Data Availability

This study is based on public databases and the references are listed in Table 1.

Competing Interests

The authors declare that they have no conflict of interest.

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Tables

Ref. No.	Product name & type	Documentation
1	BALTICSEA_REANALYSIS_PHY_003_011 Model reanalysis	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-BAL-PUM-003-011.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-BAL-QUID-003-011.pdf
2	C3S ERA5 Model reanalysis	CC3S ERA5 (2017); ECMWF: ERA5 data documentation [accessed 13.08.2022] https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation
3	BMIP river discharges River runoff	Väli et al. (2019)

Table 1. CMEMS and non-CMEMS products used in this study, including information on data documentation.

	BS	BOB	BOS	GOF	GOR	KAT	NBP	SBP
BS	1.00							
BOB	-0.38	1.00						
BOS	0.06	0.57	1.00					
GOF	0.11	0.01	-0.08	1.00				
GOR	0.13	-0.03	-0.07	-0.09	1.00			
KAT	0.42	-0.04	-0.03	-0.10	0.30	1.00		
NBP	0.78	-0.64	-0.22	0.28	-0.17	0.01	1.00	
SBP	0.88	-0.65	-0.25	-0.08	0.13	0.21	0.79	1.00

Table 2. Correlations table of the FWC between the sub-basins (Fig. 1) of the Baltic Sea (data ref. 1, Table 1).

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Figures

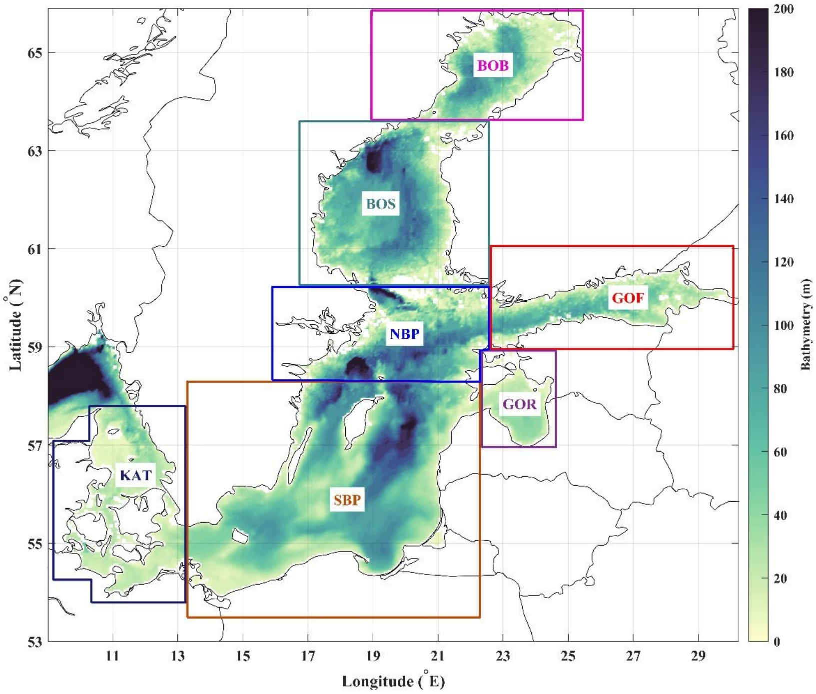

Figure 1. Map of the Baltic Sea depth distribution (data ref. 1., Table 1). Boxes show the boundaries where the freshwater content for different sub-basin is calculated. The abbreviations which are used for the sub-basins are following: KAT - Kattegat, SBP - Southern Baltic Proper, NBP - Northern Baltic Proper, BOS - Bothnian Sea, BOB - Bay of Bothnia, GOF - Gulf of Finland, GOR, Gulf of Riga.

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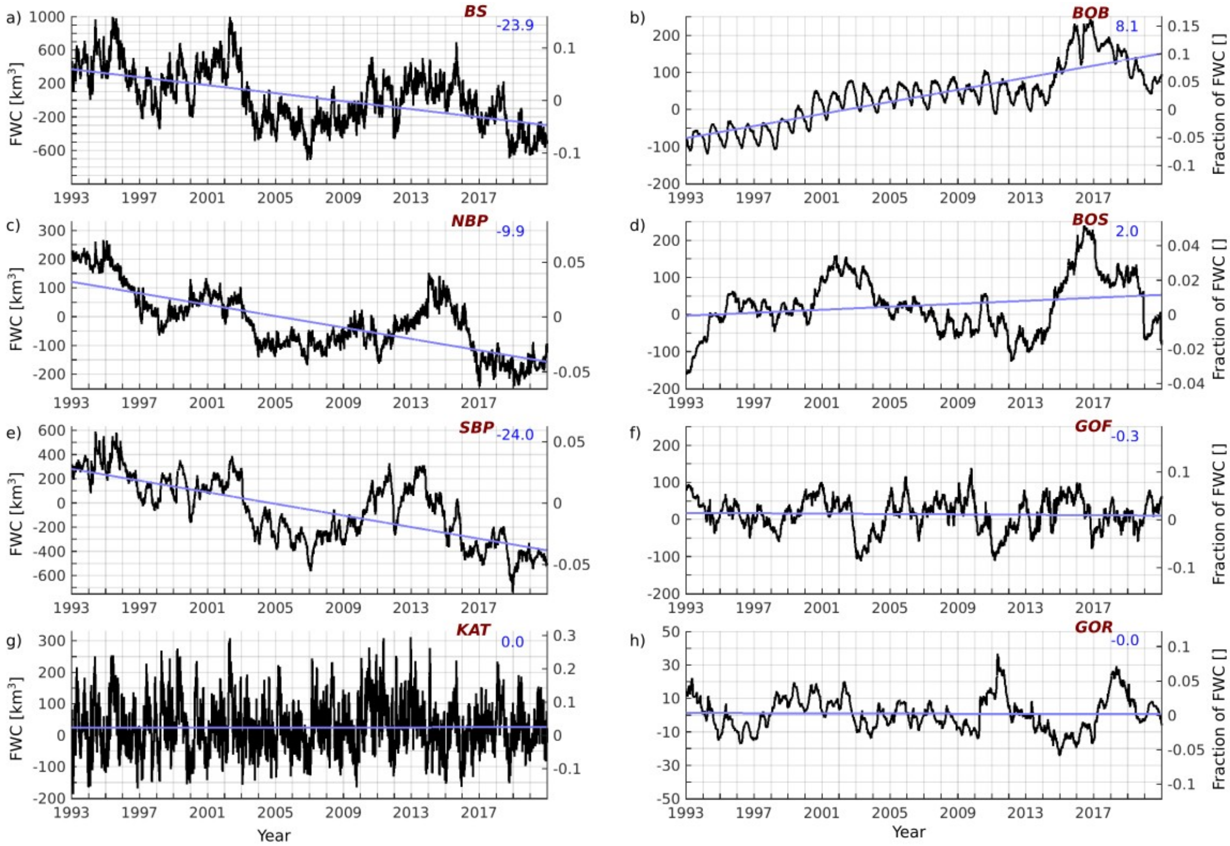

Figure 2. FWC timeseries in the Baltic Sea (a) and in different sub-basins (b-h). The trend of FWC in the corresponding basin is shown in the upper right corner (km³ per year) and plot using the blue line (data ref 1, Table 1).

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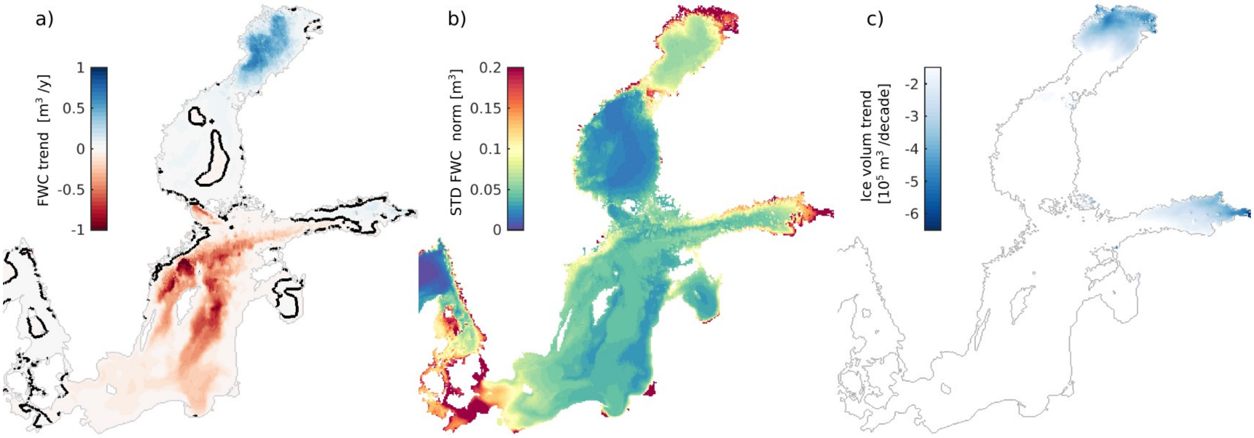

Figure 3. Trends (a) and depth normalized standard deviation of the FWC (b). Trend of the ice volume (c). Data reference 1 (Table 1).

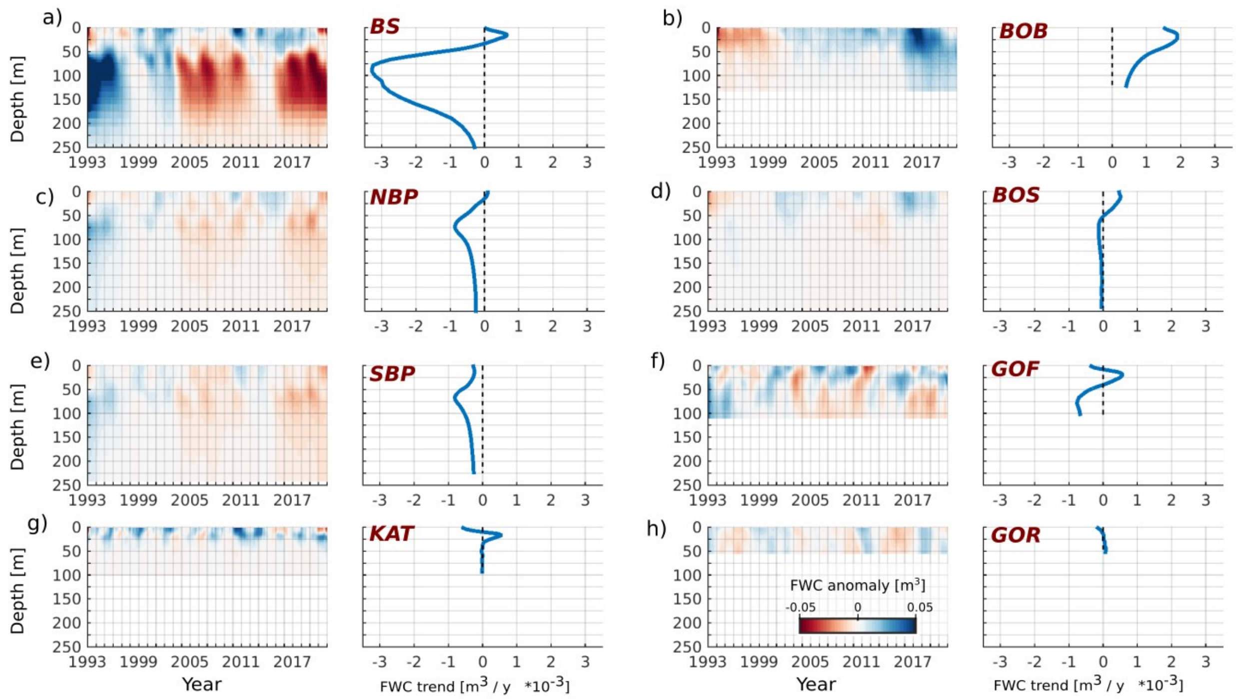

Figure 4. The vertical distribution of horizontal mean FWC anomaly and corresponding trends for each Baltic Sea sub-basin (data ref. 1, Table 1).

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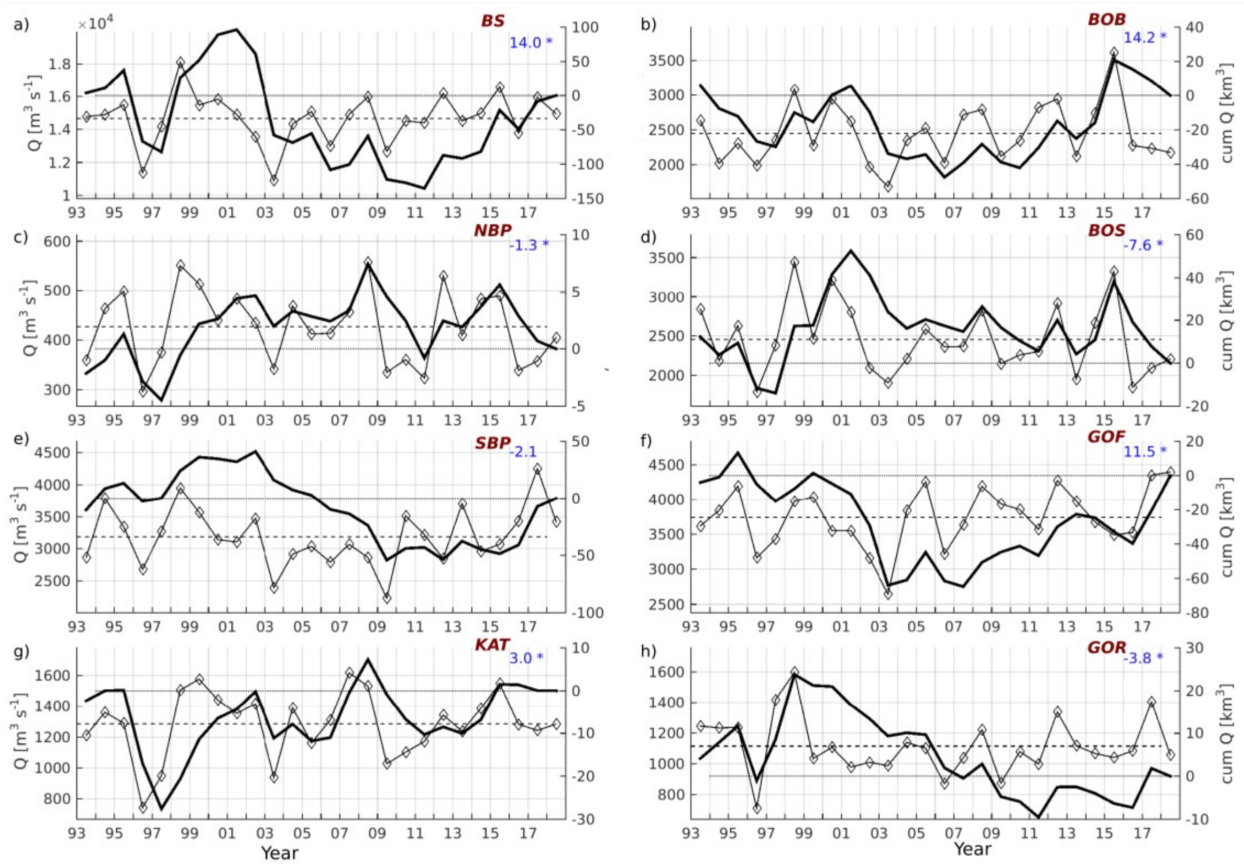

Figure 5. The annual mean runoff (left axis, diamonds) and cumulative anomaly of the mean runoff (thick line). Trends of runoff shown in upper right corner (m^3s^{-1} per year). Asterix marks the p-value >0.05. (data ref. 3, Table 1)

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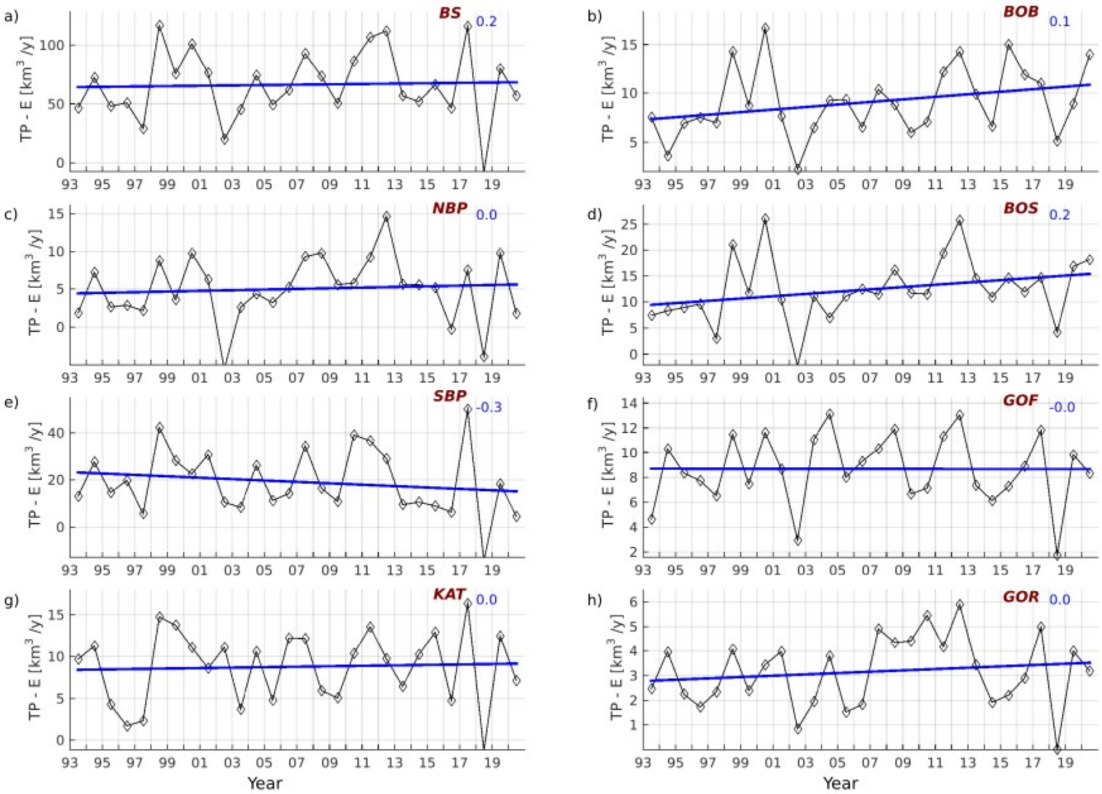

Figure 6. The annual net precipitation (precipitation - evaporation). Tendencies (km^3 year^{-1} per year) shown in upper corner and plot as blue line. (data ref. 2, Table 1)

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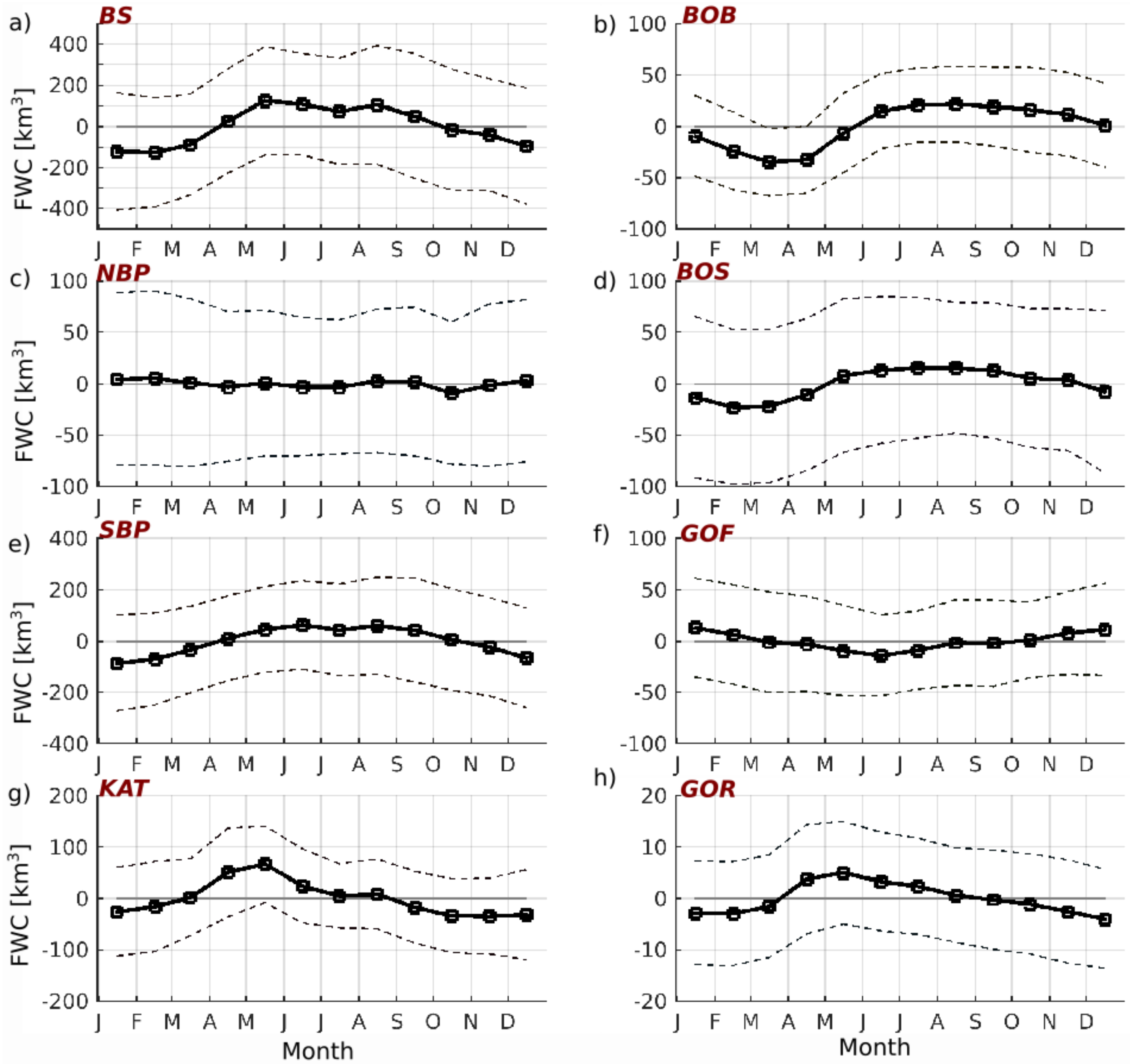

Figure 7. Seasonality of detrended FWC in the different Baltic Sea sub-basin. (data ref. 1, Table 1)

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