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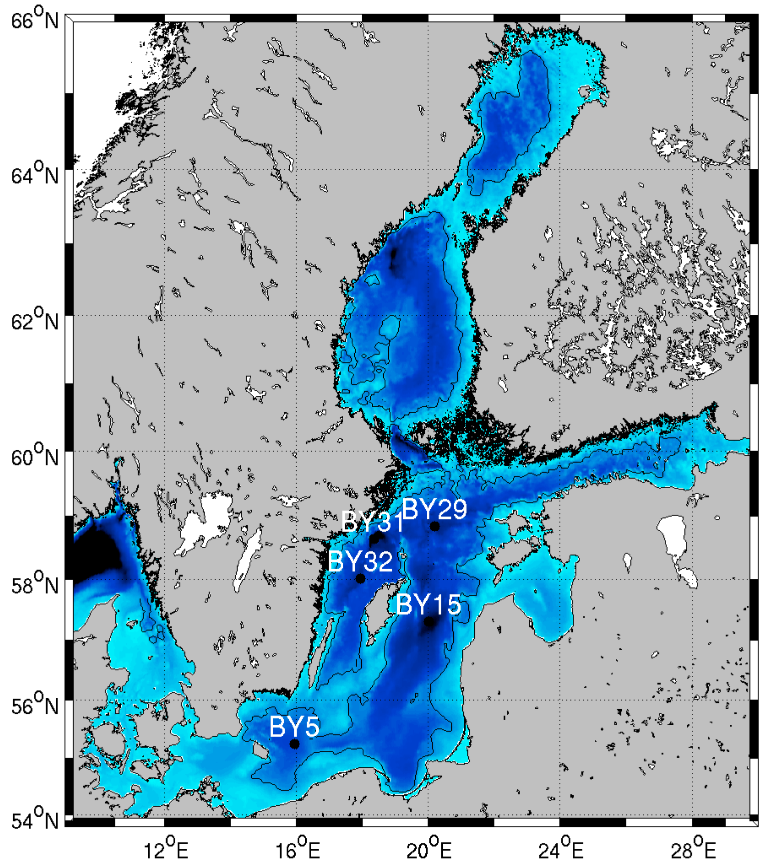

Front:
Baltic Sea bathymetry with 50 m isodepth from model domain and location of monitoring stations.

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Key words/sök-, nyckelord

Baltic Sea, RCO, numerical modelling, halocline depth, salinity

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Sammanfattning. Variationer i Östersjöns salthalt och haloklindjup under perioden 1961-2007 har studerats med hjälp av Rossby Centre Ocean Model. De största trenderna i måndadsmedelvärdet av medelsalthalten i de översta 15 m hittades i Rigabukten samt i egentliga Östersjön. I de nordligaste delarna av Östersjön kunde ej någon signifikant trend påvisas. Perioden 1970-1975 uppvisade en grund haloklin, emedan en djup haloklin kunde identifieras under perioden 1990-1995. Skillnaden i djup mellan de båda perioderna var över 15 m i egentliga Östersjön. Modellsimuleringarna antyder att medelytsalthalten i Östersjön är rumsligt styrd av den ackumulerade flodtillrinningen, medan salthalten under haloklinen i egentliga Östersjön styrs av den zonala medelvinden och den absoluta vindhastigheten. Den zonala vindhastighetens påverkan på det genomsnittliga haloklindjupet i egentliga Östersjön är måttlig och flodtillrinningens påverkan är låg.

1. Introduction

The circulation of the brackish Baltic Sea is estuarian and characterized by (a) water exchange through the Danish Straits (b) bottom topography (c) river discharge and (d) atmosphere-ice-ocean interaction. The comparatively low salinity of the Baltic Sea is a balance between the limited water exchange with the North Sea and the large freshwater input from rivers plus precipitation minus evaporation. The low frequency variations in river runoff and wind field over the Baltic Sea are causing significant changes in the salinity of the Baltic Sea as well. *Meier and Kauker* [2003a]; *Meier et al.* [2003]; *Kauker and Meier* [2003] performed several experiments on Baltic Sea salinity sensitivity on different parameters with a high-resolution three-dimensional ocean model, while others have used either a box model [*Omstedt and Axell*, 1998, 2003] or hydrographic observations [*Winsor et al.*, 2001; *Rodhe and Winsor*, 2002]. The response of salinity to the changes in river runoff is 35 years according to model simulations, while the impact to changes in wind fields or sea level in the Kattegat is much faster [*Meier*, 2005]. The shortest time scale, which is important for climatological scales is in the order of some days [*Kauker and Meier*, 2003], when major Baltic inflows occur [*Mätthaus and Franck*, 1992; *Fischer and Mätthaus*, 1996; *Lass et al.*, 2003].

The large interannual salinity variations in the Baltic Sea have been well documented and reproduced earlier by the model simulations. For instance at least two exceptionally long stagnation periods (during 1920s and 1980s) and similarly periods with very high salinity (in 1916-1920, 1948-1952 and in the late 1970s/early 1980s) were found for the last century (see *Meier and Kauker* [2003a], their Figure 8). On the other hand, the impact of the low or high salinity to different physical properties of the Baltic Sea (volume transports, freshwater distribution, halocline ventilation) is yet not fully understood, although this knowledge will give additional information for future scenarios. In this report we analyze some of the changes in physical properties of the Baltic Sea simulated with the Rossby Centre Ocean model with our focus on the changes in salinity and permanent halocline depth.

The outline of this report is as follows. In Section 2 we give an overview of the model and methods used. In Section 4 we show the varibility of Baltic salinity and halocline depth. In Section 5, we discuss the impact of different parameters to the Baltic Sea halocline depth and a summary and conclusions are given in Section 6.

2. Material and methods

2.1. Model setup

In this study, the three-dimensional Rossby Centre Ocean model (RCO) is used. RCO has been used previously for various ocean and climate studies [e.g. *Meier*, 2002a, b; *Meier and Kauker*, 2003a, b; *Meier et al.*, 2004] and is described in more detail in *Meier* [2001], *Meier et al.* [2003], *Kauker and Meier* [2003] and *Meier* [2007].

The ocean model is a regionalized version of the Ocean Circulation Climate Advanced Model (OCCAM) [*Webb et al.*, 1997], based on Bryan-Cox-Semtner primitive equation ocean model. RCO is coupled to a Hibler-type sea ice model and the subgrid-scale mixing in the ocean model is parametrized using a k-ϵ type turbulence closure scheme with flux boundary conditions [*Meier*, 2001]. The deep water mixing is assumed to be inversely proportional to Brunt-Väisälä frequency with a proportionality factor a=$1 \cdot 10^{-7}$m^2 s^{-2}, which is in good agreement with the observations in the eastern Gotland Basin [*Lass et al.*, 2003] A flux-corrected, monotonicity preserving transport (FCT) scheme ([*Gerdes et al.*, 1991]) is embedded without explicit horizontal diffusion.The barotropic and baroclinic modes in the model are separated with the timesteps 15s and 150s, respectively.

The model domain is based on the topography taken from *Seifert and Kayser* [1995] and covers the Baltic Sea with horizontal resolution of 2 nautical miles and in 41 vertical levels with varying layer thicknesses from 3 m close to the surface to 12 m near the bottom. In the northern Kattegat an open boundary is used, where in case of inflow temperature and salinity values are nudged towards observed climatological profiles in the southern Kattegat and in case of outflow a modified Orlanski radiation condition is used [*Stevens*, 1991]. The sea level elevation at the boundaries is taken from daily tide gauge data. A BBL model is embedded to allow the direct communication between bottom boxes and step-like topography [*Beckmann and Döscher*, 1997] and this improves the simulation of gravity driven dense bottom flows [*Meier et al.*, 2003].

River runoff data are taken from *Bergström and Carlsson* [1994] and updated with results from a large-scale hydrological model [*Graham*, 2004]. Air temperature, wind, cloud cover, sea level pressure, humidity and precipitation are required as surface boundary, no data assimilation is applied. The atmospheric conditions are taken from Rossby Centre Regional Atmosphere model (RCA) at 25 km horizontal resolution [*Samuelsson et al.*, 2011; *Meier et al.*, 2011]. The boundary conditions for the atmospheric model are taken from ERA40 reanalysis data [*Uppala et al.*, 2005] updated with operational ECMWF data. This data set allows for hindcast simulations covering the period 1961-2007. In previous studies, the atmospheric model RCA has been used succesfully as boundary condition for the ocean model RCO [e.g. *Döscher et al.*, 2002].

2.2. Halocline depth

The mean halocline depth during a specific period is defined as the maximum of the first derivative of the mean salinity during the same period:

$$H_{halocline}(x,y) = max(\frac{\Delta S(x,y,z)}{\Delta z}),$$

where $H_{halocline}(x,y)$ is the mean halocline depth, $S(x,y,z)$ is the mean salinity during the period at location (x,y), and z is depth. The salinity gradient for the grid cell is numerically calculated using the difference between the salinities in two vertically neighbouring grid cells divided by the distance between these grid cells. The mean vertical salinity gradient at locations with large runoff impact has two maxima, where the first is due to the increased freshwater content in the surface layers and the second is the perennial halocline. In order to study only the changes of the perennial halocline, we assume that the halocline is located deeper than 30 m and should not appear in areas with depth less than 50 m. The method is summarized in Figure 1 with mean salinity profiles taken from monitoring station BY15 for two different periods characterized by shallow (1970 to 1975) or deep halocline (1990 to 1995). The periods with significantly different halocline depths were identified from halocline depth time-series for different stations in the Baltic Sea.

In order to compare the impact of freshwater to the halocline depth, we calculate the freshwater content in the Baltic Sea using:

$$f(x,y) = \int_x \int_y \int_z \frac{max([S_{ref} - S(x,y,z)],0)}{S_{ref}} dxdydz,$$

where $f(x,y)$ is the freshwater content, which is needed to dilute the water with salinity S_{ref} to obtain the salinity $S(x,y,z)$ at location (x,y) on depths z. The reference salinity is the Kattegat deepwater salinity $S_{ref} = 33$ g/kg.

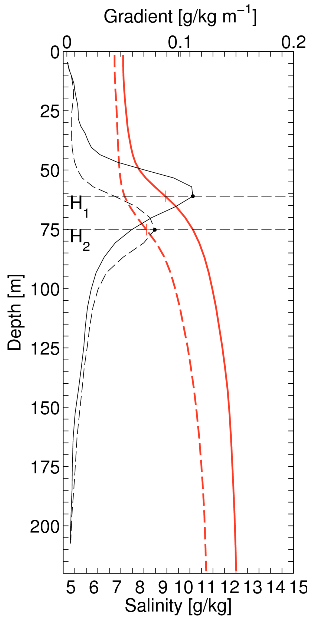


Figure 1. Mean salinity profiles (red) at BY15 during 1970-1975 (solid line) and 1990-1995 (dashed line) with the corresponding salinity gradients (black line). The mean halocline depths during the periods are denoted by horizontal lines (H_1 and H_2).

2.3. Statistical significance

The statistical significance of the trends for the monthly mean salinity have been analyzed using the F-statistic and the significance of the F, which is one of the most common techiniques for testing the statistical significance of regression model.

The ability of the statistical model (e.g. regression line) to simulate the variable is tested by looking the ratio of explained variability to the unexplained variability:

$$F_{statistic} = \frac{explained\ variance}{unexplained\ variance}$$

If $F_{statistic} < F_{\alpha,k,n-(k+1)}$, where α is the significance level, k the number of parameters in the statistical model and n the number of observations and the value is the F-distribution value, then the statistical model is assumed to be statistically insignificant and regression coefficients equal 0.

In case of $F_{statistic} \geq F_{\alpha,k,n-(k+1)}$, at least one of the coefficients in the regression model is assumed not to be equal to zero. The statistical significance of regression parameters (the p-value) can be calculated from the inversed F-distribution for value $F_{statistic}$ for number of regression parameters k and degree of freedom $n-(k+1)$, where p is the probability from the F-distribution.

2.4. Model evaluation

The RCO has been validated against observations in many different studies [*Meier and Kauker*, 2003a; *Meier*, 2007; *Eilola et al.*, 2011]. Hereby we highlight the findings.

The salinity in the Baltic Sea is qualitatively well reproduced in the RCO model on long time-scales. *Meier and Kauker* [2003a] was able to simulate the salinity in the monitoring station BY15 with slightly underestimating the halocline depth and decadal variations (see *Meier and Kauker* [2003a], their Fig. 7), but the minima during 1930s and 1990s and the pronounced maxima during the 1950s were simulated correctly. The mean error of daily sealevel in reconstruction at Landsort station was 3.0 cm with root mean square error of 11.2 cm and correlation between the observed and reconstructed serie 0.88. The maximum ice cover extent was also fairly well reproduced with slight overestimation and the mean difference between observed and simulated maximum ice cover extent during 1980-1998 was 9200 km^2, root mean square difference 43900 km^2 and correlation 0.92.

The results of simulations with the high-resolution RCO were validated against the observations in *Meier* [2007] and inter-comparsion between different models in the Baltic Sea in *Eilola et al.* [2011]. *Meier* [2007] concluded that the spatial variability of temperature and salinity was well reproduced by the model. Most of the observed large and medium-strength saltwater inflows occured also in the model. The simulated halocline in the Gotland Deep appeared too shallow and the surface salinity overestimated, while *Eilola et al.* [2011] reported underestimation of the surface salinity. The ability of the model to simulate the salinity in the Baltic proper has an impact to the salinity of terminal basins. *Meier* [2007] indicated that due to overestimation of Baltic proper surface salinity, the salinity in the Bothnian Sea appeared overestimated as well. Nevertheless the salinity gradients from north to south and surface to the bottom were reproduced well by the model.

The comparison between 3 different models with the same atmospheric forcing for the Baltic Sea was made in *Eilola et al.* [2011]. All models studied had problems with the northernmost parts of the Baltic Sea. The salinity in the RCO was underestimated with the largest difference in the bottom layers of the

Baltic proper (see *Eilola et al.* [2011], their Fig.6). Nevertheless, compared to the three-dimensional model ERGOM, the RCO performed better in all the stations used for validation (see *Eilola et al.* [2011], their Fig.13).

In conclusion, the temporal variatons of the Baltic Sea salinity in the RCO model are well captured and comparable with the real observations. It is possible to use the RCO model output to study the long-term changes in the Baltic Sea halocline depth and the impact of different forcing parameters to the mean halocline variability.

3. Forcing data

The main forcing factors controlling the Baltic Sea salinity and thereby the halocline depth are the mean zonal wind speed and runoff [*Meier and Kauker*, 2003a; *Kauker and Meier*, 2003]. The impact of changes in the river runoff to the Baltic Sea salinity are apparent, while the impact of the wind field is not so implicit. *Meier and Kauker* [2003a] were able to explain the stagnation periods in the Baltic Sea during periods with increased westerlies by hampered salt transport due to additional barotropic pressure gradient caused by the anomalous high sea level in the Baltic Sea.

During the simulation period the mean annual runoff was aproximately 15220 m^3s^{-1}, with considerable interannual variability (Fig. 2). The values were lower during 1967-1977 and larger during stagnation period starting from the beginning of the 1980s to the mid 1990s (values close to $16000m^3s^{-1}$) and decreased rapidly during 2000s. The runoff to the Baltic Sea has significantly large seasonal cycle – the runoff is the largest during spring and the lowest during summer and winter. The mean seasonal cycle changed slightly during the simulation period. The maximum for two periods (1961-1978 and 1979-2007) remained unchanged, while the seasonal runoff had increased remarkably for summer (months July and August) during 1979-2007.

The monthly mean zonal wind speed has significant interannual variability during the simulation period (Fig. 3). The period 1975-1980 is characterized by reduced westerly winds in the Baltic Sea area, while the period 1985-1993 is characterized by increased westerly winds. There is also a seasonal cycle within the monthly mean wind speed, but with large differences between two different time periods. The mean zonal wind speed during winters 1979-2007 was significantly higher than during 1961-1978.

The magnitude of the wind in the Baltic Sea area has also increased during 1963-2005 (Fig. 4) with a large leap in the mean wind speed during late 1980s. There is clearly pronounced seasonal cycle in the mean wind speed. The highest values are during autumn and early winter and the lowest late spring and summer season. Diversely from the mean zonal wind speed, the seasonal cycle did not differ for two different time periods. The mean windspeed had slightly increased for most of the months during 1979-2007.

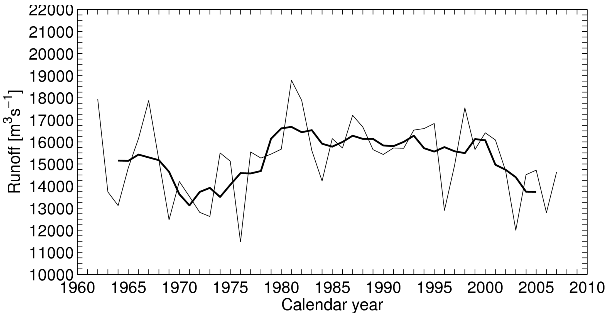
4. Results

In this section we will show the variability of the Baltic Sea salinity, halocline depth and mean vertical salinity gradient in the halocline. The subsections are based on the variability of the parameter. We will show the mean-states of different variables during different periods in chapter 4.1, the seasonal cycle in chapter 4.2 and interannual variability in chapter 4.3.

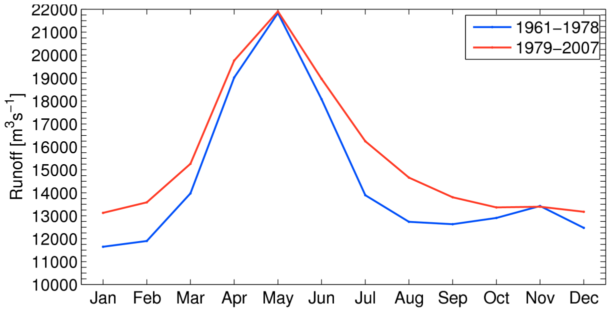
4.1. Mean distribution

4.1.1. Salinity The mean salinity averaged over the top 15 meters of the Baltic proper during 1970-1975 was larger than 7 g/kg in most of the areas (Fig. 5). In the southern Baltic proper the salinity was even higher than 7.5 g/kg, while in the northern Baltic proper the salinity was 6-6.5 g/kg. By 1990-1995, the area with salinity less than 7 g/kg had significantly increased in the northern Baltic proper and saltier water had been pushed out from the Baltic proper to the Arkona Basin, where the salinity remained over 7.5 g/kg. The upper layer salinity in the Gulf of Finland also reduced over time as the values at the entrance decreased from valuse 6-6.5 g/kg to values 5.5-6 g/kg. The difference between the periods was low in the northern parts of the Baltic Sea.

The mean salinity averaged from the 65 m to the sea bottom (the below halocline salinity) is the largest in the Bornholm Basin and decreases to the north in other parts of the Baltic Sea. The mean below halocline salinity in the Baltic proper was larger than 10.5 g/kg and in the Gulf of Finland higher than 9 g/kg, while in the Bothnian Sea it was 6-6.75 g/kg. The lowest values (less than 3.75 g/kg) were in the Bothnian Bay By 1990-1995, the mean below halocline salinity had decreased more than 1.4 g/kg in the Baltic Proper and more than 1.8 g/kg in the Gulf of Finland to the values larger than 8.25 and 7.5 g/kg, respectively. The largest differences more than 2 g/kg

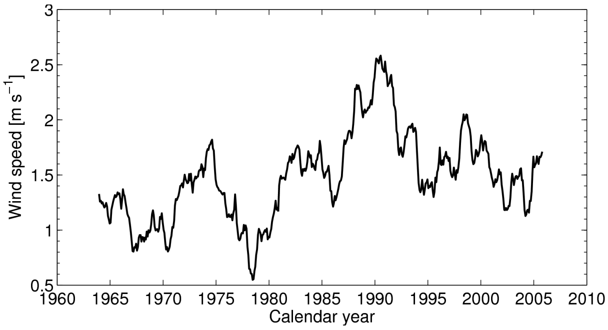


(a) *Interannual variability*

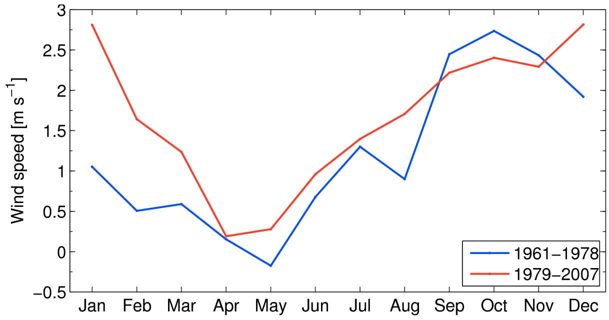


(b) *Seasonal cycle*

Figure 2. Runoff forcing during simulation period 1961-2007 with (a) annual mean runoff to the Baltic Sea and (b) the mean seasonal cycle for two different periods – 1961-1979 and 1979-2007

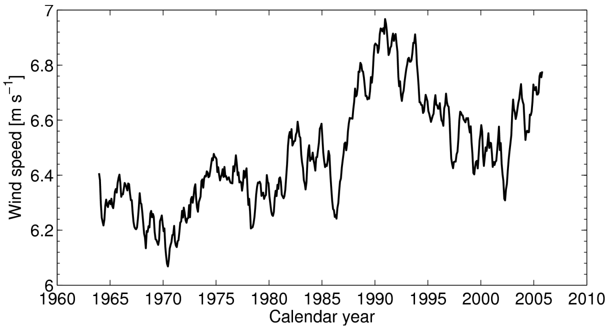


(a) *Interannual variability*

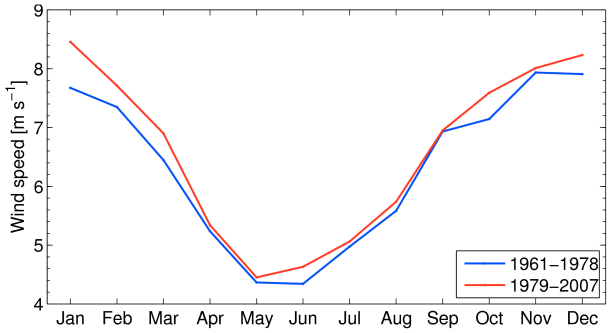


(b) *Seasonal cycle*

Figure 3. Mean zonal wind forcing during simulation period 1961-2007 with (a) monthly mean zonal wind speed in the Landsort station and (b) the mean seasonal cycle for two different periods – 1961-1979 and 1979-2007

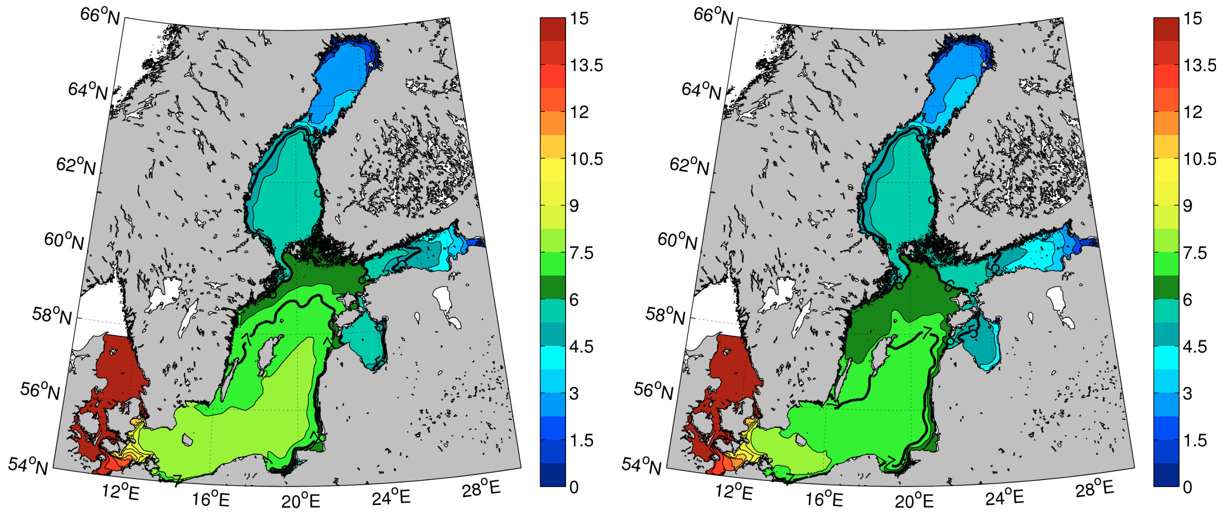


(a) *Interannual variability*



(b) *Seasonal cycle*

Figure 4. Mean zonal wind forcing during simulation period 1961-2007 with (a) monthly mean zonal wind speed in the Landsort station and (b) the mean seasonal cycle for two different periods – 1961-1979 and 1979-2007



(a) *1970-1975* (b) *1990-1995*

Figure 5. The volume averaged salinity over the top 15 meters in the Baltic Sea during (a) low and (b) high halocline depth period. Units g/kg.

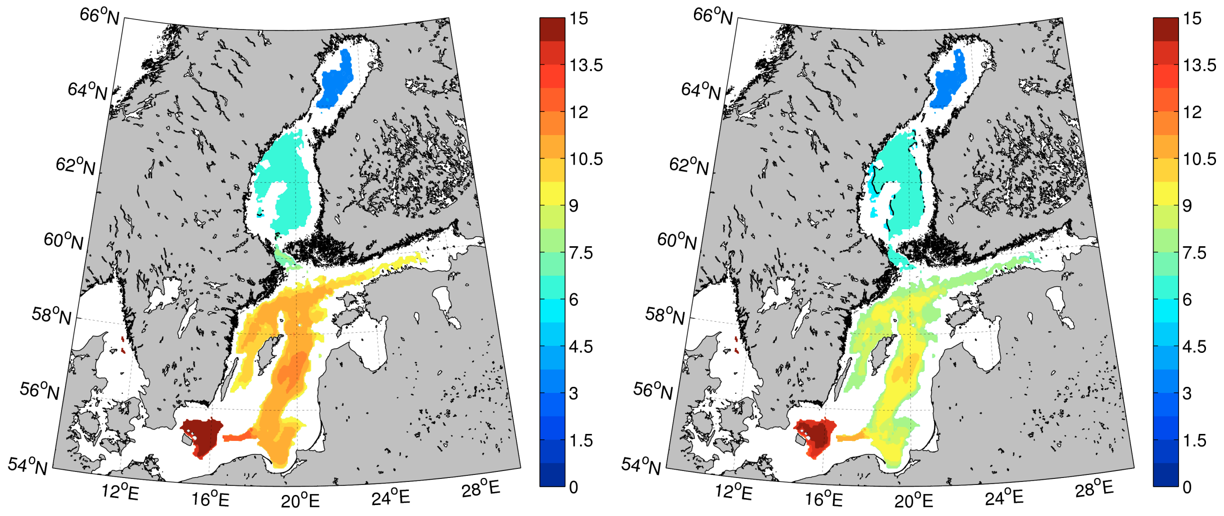
were in the northern Baltic proper. Salinity decrease was less than 0.6 g/kg in the Bothnian Sea, while insignificant changes were in the Bothnian Bay.

4.1.2. Halocline depth The mean halocline depth in the Baltic proper during period with shallow halocline (1970-1975) was 52-60 meters as seen from mean halocline depth maps (Fig. 7). The halocline was located deeper in the Eastern Gotland Basin and shallower in the Western Gotland Basin, while the deepest halocline (depths over 65 m) was in the Slupsk Furrow, Gdansk Bay and also in the northern Baltic proper close to the entrance to the Gulf of Finland.

In the Bornholm Basin, the mean halocline depth was 52-56 m, with the largest depths, 62-65 m, in the southern part. In the Gulf of Finland, the halocline depth reduced towards Neva Bay – the halocline was located at depths up to 68 m at the entrance to the Gulf, while in the central part the mean halocline depth was 50-53 m and 35-44 m in the eastern part. Especially high halocline depth was found during shallow halocline period in the land sea (entrance to the Bothnian Sea), which extended to the central Bothnian Sea at depths more than 62 m, while in the eastern and northern parts of the basin the halocline depth was preferably 59-62 m. In the northern parts of the Bothnian Bay the mean halocline depth was from 47 to 56 m, exceeding 65 m in the southern part.

During the deep halocline period (1990-1995) the mean halocline depth in most of the Baltic proper was over 74 m. The highest values up to 80 m were in the northern Baltic proper and at the entrance to the Gulf of Finland, while in the Western Gotland Basin the mean halocline depth had increased to 65-71 m and in the Eastern Gotland Basin to 68-74 m compared to the period 1970-1975. In the western part of the Gulf of Finland the halocline depth had increased to the values over 68 m, while the changes in the central and eastern part were not large. In the southern part of the Gulf of Finland the mean halocline depth was instead shallower with values 38-41 m compared to the period 1970-1975, when the mean halocline was at 56-62 m depth. The most extensive changes in the halocline depth were in the northern Bothnian Sea, where the halocline depth had increased to the values at 68-74 m in most of the region.

The differences in the halocline depth between two periods are summarized on Fig. 7c). In the Bornholm basin the mean halocline depth did not change, while in the Baltic proper and northern Bothnian Sea the changes were significant. In the Gdansk Basin the halocline depth increased more than 5 m and at some of the locations even more than 10-12 m. In the southern and central parts of the Eastern Gotland Basin the changes were larger than 12 m, while in the northern part of Western Gotland Basin the halocline depth increased more than 17.5 m, with the most preferred change close to 15 meters.



(a) *1970-1975* (b) *1990-1995*

Figure 6. The volume averaged salinity from 65 m to the bottom in the Baltic Sea during (a) low and (b) high halocline depth period. Units g/kg.

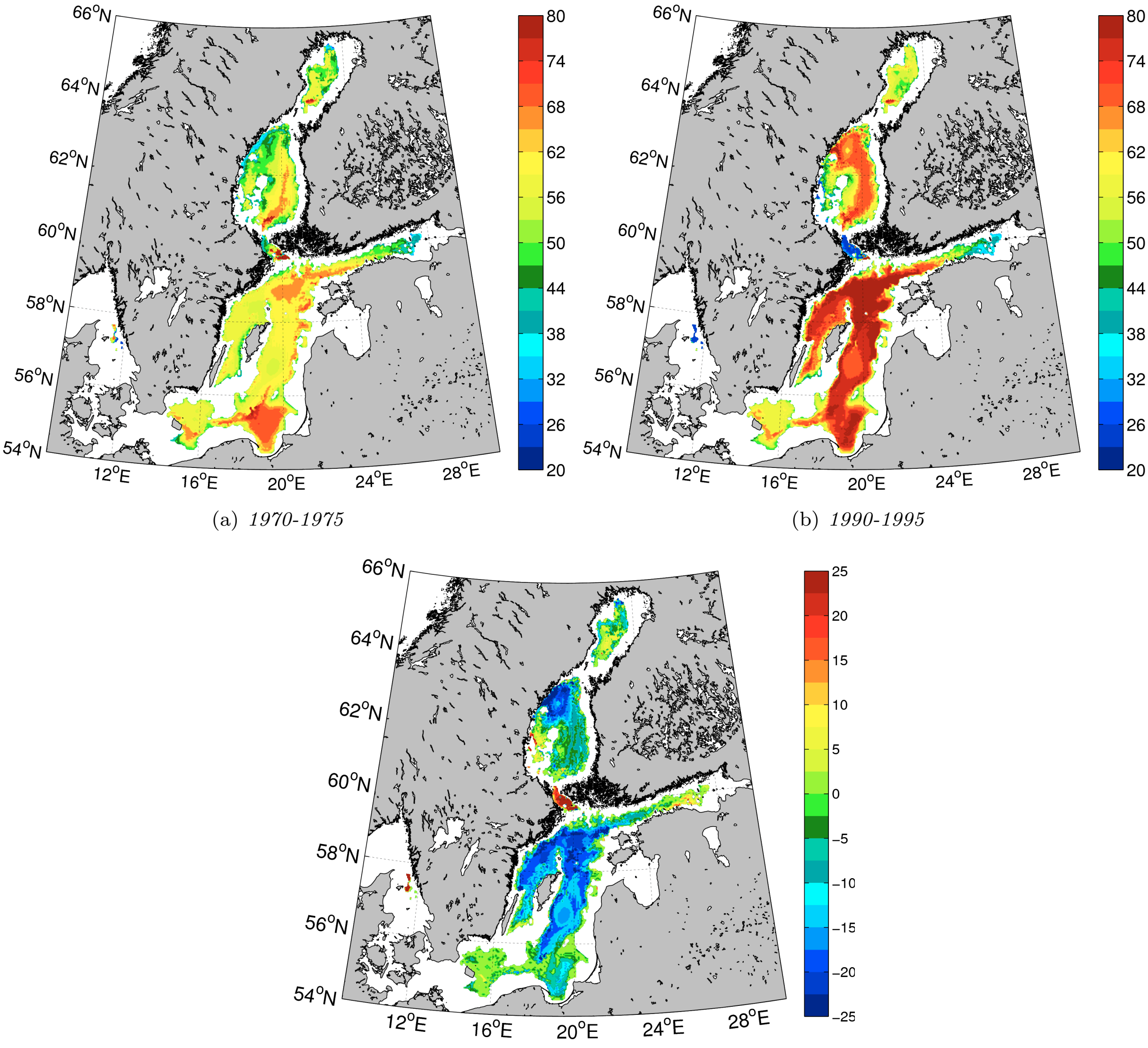
4.1.3. Halocline vertical salinity gradient The measure of the halocline strength is the vertical salinity gradient. The mean vertical salinity gradients for different periods are shown on Figure 8 and the difference between the periods on Figure 8c. The mean vertical salinity gradient was the largest (over 0.5 g/kg m^{-1}) in the basins with the highest salinity (Arkona and Bornholm) and within the basins was characterized with south to north increase.

During both the shallow and deep halocline depth periods, the mean vertical salinity gradient in the halocline was significantly smaller in other basins of the Baltic Sea with lowest values in the northernmost parts. The mean vertical salinity gradient decreased the most in the Gulf of Finland and in the transition area between Eastern Gotland Basin and Gdansk Basin with values up to 0.05 g/kg m^{-1}. The increase in the mean vertical salinity gradient was in the Slupsk Furrow (values 0.03 g/kg m^{-1}) and in central parts of the Arkona Basin (values more than 0.05 g/kg m^{-1}), while the changes in the northernmost parts were very low except for some locations in the Bothnian Sea, where gradient decreased more than 0.015 g/kg m^{-1} and in Bothnian Bay, where the salinity gradient increased more than than 0.05 g/kg m^{-1}. In the Baltic proper the decrease of mean vertical salinity gradient was 0.025 to 0.035 g/kg m^{-1} with the largest change in the Eastern Gotland Basin.

4.2. Seasonal cycle

4.2.1. Salinity The seasonal cycle of salinity in different basins of the Baltic Sea are summarized with maps of mean salinity difference between winter and summer during different periods (Fig. 9). The seasonal cycle is the largest in the northern Baltic Proper and the Gulf of Finland, where the difference between the mean season salinities averaged over the top 15 m exceed 0.5 g/kg. Pronounced seasonal cycle extends to the central eastern Gotland Basin, where the mean season salinity difference is larger than 0.25 g/kg. In the northern parts of Baltic Sea, the seasonal cycle is seen in the northern parts of Bothnian Sea and northern part of Bothnian Bay. The differences in seasonal cycle during 1970-1975 and 1990-1995 are to great extent minor. During both periods, the most indicated seasonal cycle is in northern Baltic Proper and Gulf of Finland. The largest differences between the periods are in Eastern Gotland Basin, where the largest salinity differences have moved from the western part to the east.

4.2.2. Halocline depth The seasonal cycle of the permanent halocline is rather low. The differences between climatological summer and winter mean halocline depth are less than 10 m in most of the Baltic Sea. The largest differences are in the Eastern Gotland Basin, where the large gyre occurs due to Ekman pumping. The difference in the permanent

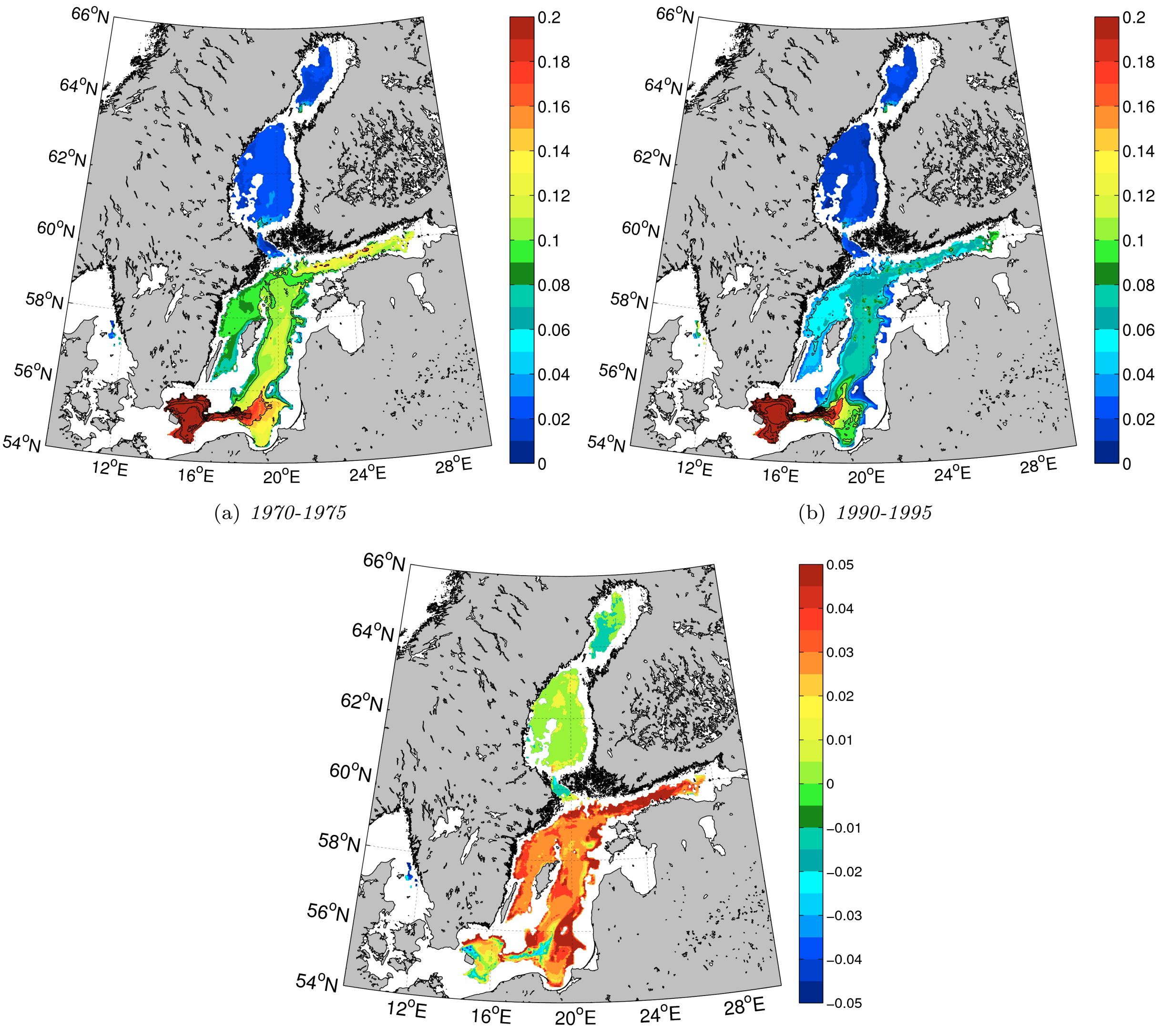


(a) *1970-1975*

(b) *1990-1995*

(c) *Difference*

Figure 7. The mean halcoline depth in meters during (a) 1970-1975 (low halocline depth period) and (b) 1990-1995 (high halocline depth period) with (c) the difference between the periods. Units m.

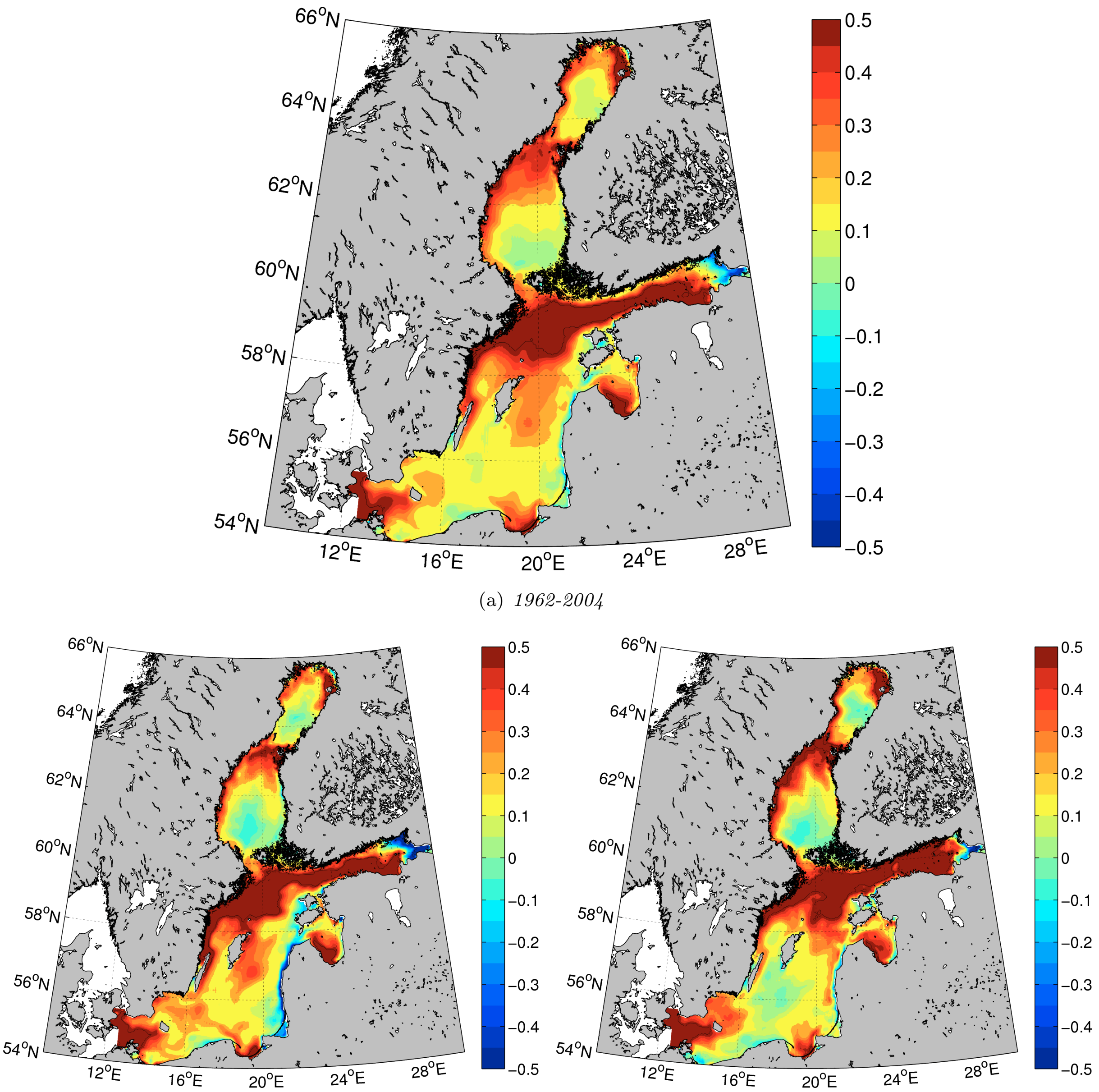


(a) *1970-1975*

(b) *1990-1995*

(c) *Difference*

Figure 8. The mean vertical salinity gradient in the halocline for period (a) 1970-1975 and (b) 1990-1995 with (c) the difference between the periods. Units g/kg m^{-1}.



(a) *1962-2004*

(b) *1970-1975*

(c) *1990-1995*

Figure 9. The difference between winter and summer mean salinities averaged over the top 15 m during (a) 1962-2004, (b) 1970-1975 and (c) 1990-1995. Units g/kg.

halocline depth due to the cyclonic gyre are more than 8 m. The difference between the mean seasonal permanent halocline depth was also large in the eastern parts of Western Gotland Basin, where the permanent halocline is lifted for winter season more than 6 m.

The seasonal cycle of mean halocline depth is more pronounced during period with the deep halocline. The differences between summer and winter mean halocline depth in the Baltic proper exceed 12 m in southern Eastern Gotland Basin and eastern parts of Western Gotland Basin.

However, the location of the maximum salinity gradient has significant seasonal cycle in most of the areas in the Baltic Sea as shown by *Meier* [2007]. In this study, we focused only on the maximum located below 35 m and thereby to the seasonal changes in the permanent halocline depth.

4.2.3. Halocline vertical salinity gradient The mean halocline vertical salinity gradient has well pronounced seasonal cycle in areas affected by the freshwater inflow or Ekman pumping (the basinscale gyre in the Eastern Gotland Basin). In the latter, the mean halocline vertical salinity gradient is the largest during late winter/early spring and the weakest in the autumn with the difference between February maximum and October minimum more than 0.06 g/kg m^{-1} (in station BY15).

The annual cycle of the halocline depth and vertical salinity gradient is shown on Figures A1 to A6. The climatological halocline depth was the shallowest during wintermonths December and January (Fig. A1a and l) and the deepest by April or May. The shallowing of the halocline depth started in August, when the halocline in the Eastern Gotland basin and Western Gotland basin is lifted. During period with shallow halocline depth, the annual cycle was similar – the halocline depth was the lowest in January and the highest somewhere in May or June in the Eastern Gotland basin. In the central and southern parts of Western Gotland basin, the halocline remained deep until October.

The mean vertical salinity gradient is the strongest during winter and spring and the weakest during the summer and autumn, while the minimum and maximum appeared during October-November and February-March, correspondingly.

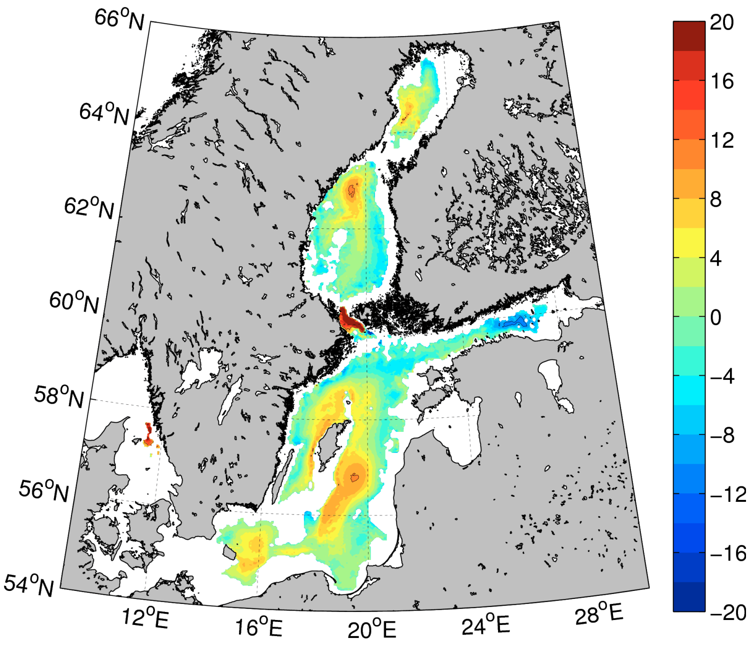
4.3. Interannual variability

4.3.1. Salinity The salinity in the Baltic Sea has quite large low- and high-frequency variations in different basins of the Baltic Sea(Fig. 12). The seasonal variability is caused by the increased freshwater input during spring, but the interannual and interdecadal variations by the low-frequency changes in wind fields and runoff [*Meier and Kauker*, 2003a]. The monthly mean salinity averaged over the top 15 m (surface salinity) is the highest in the southern Baltic Sea and transition area between the southern and northern parts – land sea and Finnish Archipelago, while the overall mean is the closest to the Eastern Gotland Basin mean (Fig.12a).

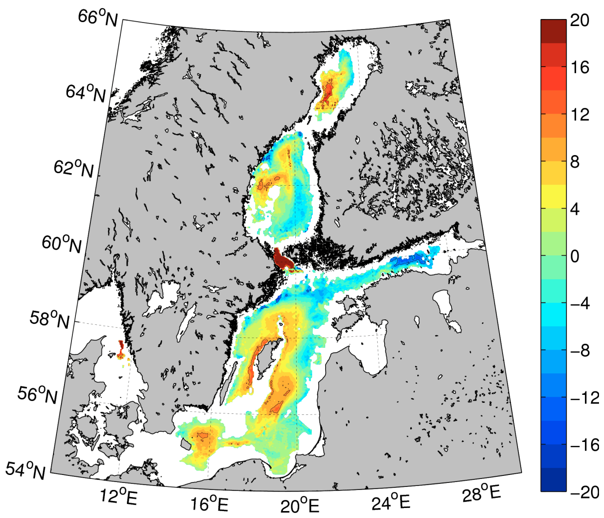
In all the basins the surface salinity was the highest during the late 1970s/early 1980s, while the decrease in the Gulf of Riga started 5 years later compared to the other basins. The smallet values occured in 2003, the salinity started to increase in the Baltic Sea afterwards. The differences between the low and high salinity periods were upto 0.8 g/kg in the southern and eastern parts of the Baltic Sea, while the smallest differences (less than 0.5 g/kg) were in the northernmost parts of the Baltic Sea.

The overall trend of the Baltic Sea surface salinity (averaged top 15 m) during 1962-2007 is summarized and shown on Figure 13, while the trends for the seasonal mean surface salinity are shown on Figure 14. The statistical significance has been tested with the F-test (see Section 2.3) and trend coefficient removed from the maps if p¿0.05. The negative trend has been the largest in the Gulf of Riga, where the decrease rate was almost 0.2 g/kg decade^{-1}. In the Baltic proper the decrease has been 0.14-0.16 g/kg decade^{-1} and in the Gulf of Finland with Bothnian Sea close to 0.1-0.15 g/kg decade^{-1} with higher decrease rate at the northern side of the entrance to the Gulf of Finland. The interannual changes in the salinity were negligible in the northernmost part of the Baltic Sea (Bothnian Bay), where the salinity is constantly low due to high freshwater input from rivers.

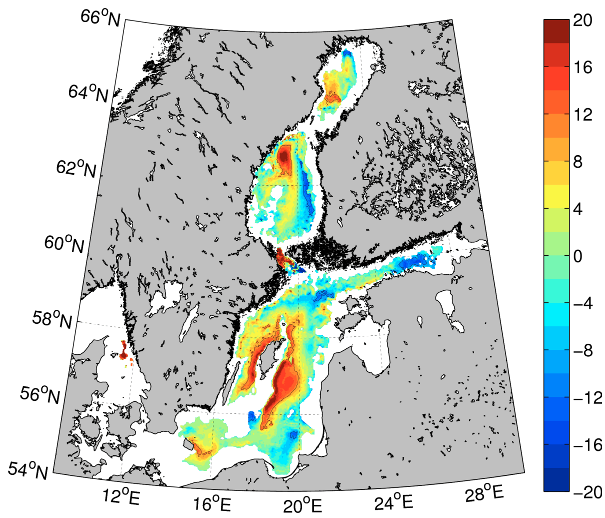
The mean seasonal surface salinity had also decreased the largest in Gulf of Riga and the Baltic Proper. Statistically insignificant trends were found for some areas in the Gulf of Finland and Bothnian Bay. Interestingly strong trend was found in the mean autumn salinities at the northern coast of the Gulf of Finland. The main differences between the season trends in the Baltic proper is that the decrease has been homogenously large in all parts, while for the



(a) *1962-2004*

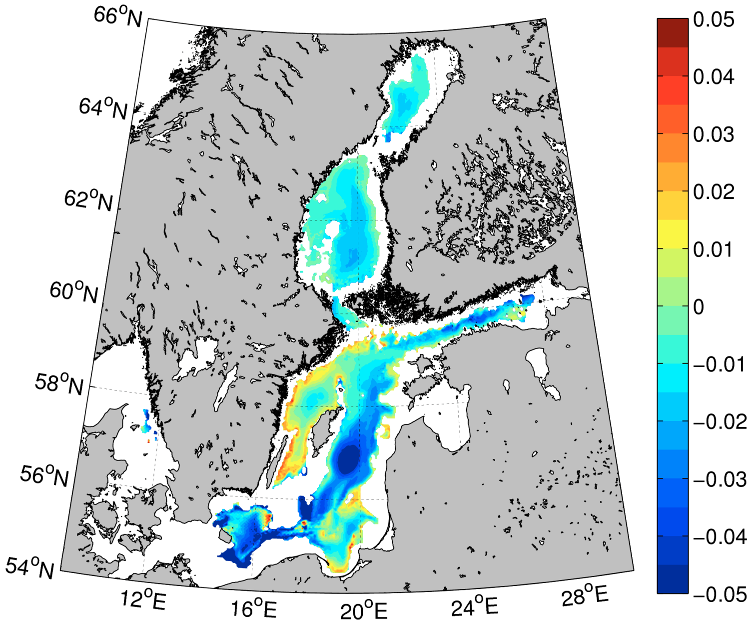


(b) *1970-1975*

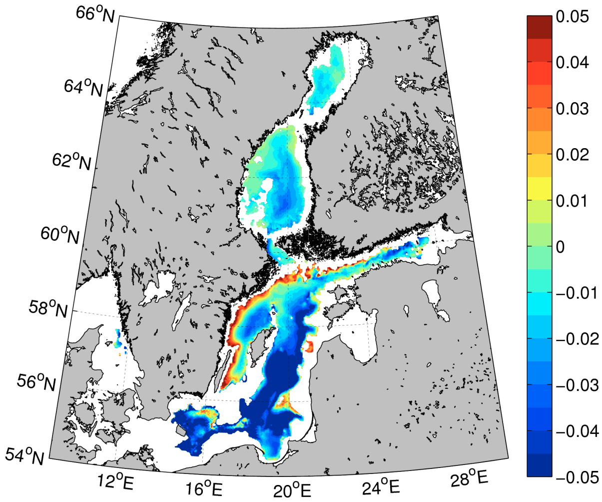


(c) *1990-1995*

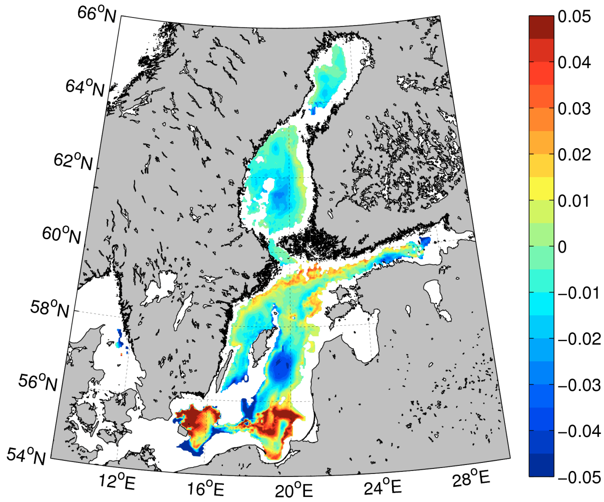
Figure 10. The difference between summer and winter mean halocline depths during (a) 1962-2004, (b) 1970-1975 and (c) 1990-1995. Units m.



(a) *1962-2004*

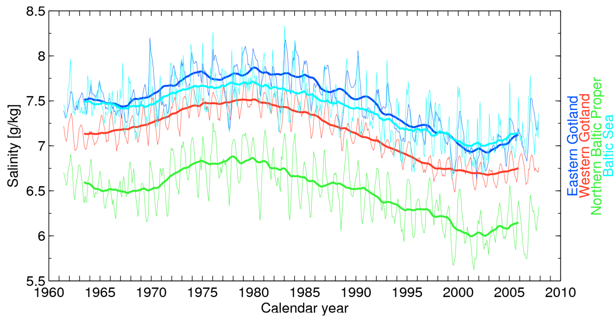


(b) *1970-1975*

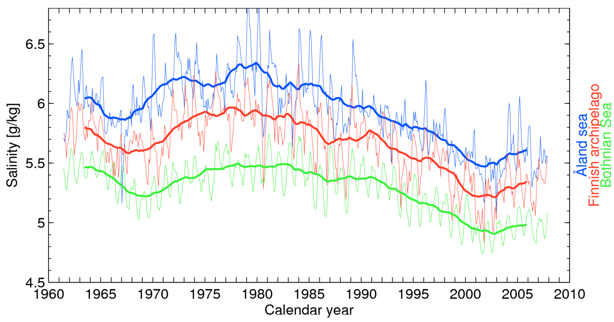


(c) *1990-1995*

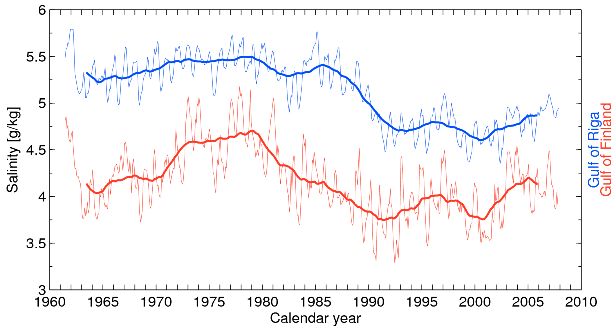
Figure 11. The difference between summer and winter mean vertical salinity gradient in the halocline during (a) 1962-2004, (b) 1970-1975 and (c) 1990-1995. Units g/kg m^{-1}.



(a) *Southern Baltic Sea*



(b) *Northern Baltic Sea*



(c) *Eastern Baltic Sea*

Figure 12. The monthly mean volume average salinity over the top 15 metres (thin line) with the 4-year running mean (bold line) for different basins. Units g/kg.

spring salinity the trend was larger in eastern and for the summer and autumn in the eastern parts of the basin.

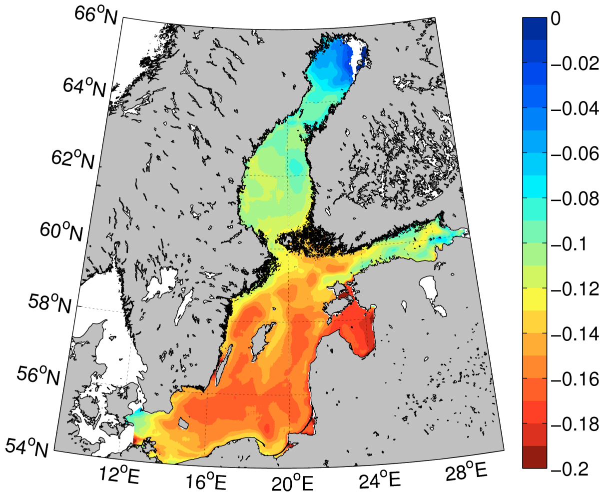


Figure 13. Statistically significant trend in the monthly mean salinity averaged over the top 15 m during 1962-2007 (p¡0.05). Units g/kg decade^{-1}.

4.3.2. Halocline depth and vertical salinity gradient

The mean halocline depth in the Baltic Sea has remarkable interannual variations (more than 30 m) in different parts of Baltic proper (Fig. 15). In several locations the permanent halocline appears deep during summer, when the freshwater has reached the Baltic Sea and shallow during winter, when the upper layer above the halocline is vertically mixed.

The low-pass filtered mean halocline depth with cut-off period of 4 years in the Baltic proper had also significant changes during the simulation period indicating the interannual variability in the mean halocline depth of the Baltic Sea. The exception was the Bornholm Basin (BY5), where the mean halocline depth remained close to 55 meters and did not show interannual variability, while the monthly variations were larger than 30 m. On the other hand, the mean halocline depth in the Baltic proper was the shallowest by 1972-1973 (up to 55 m) and increased during stagnation period in 1980s to the values close to 75 m by 1991-1992 in all monitoring stations (see Figure 15). The halocline depth decreased to the values close to 60 m during 2000s.

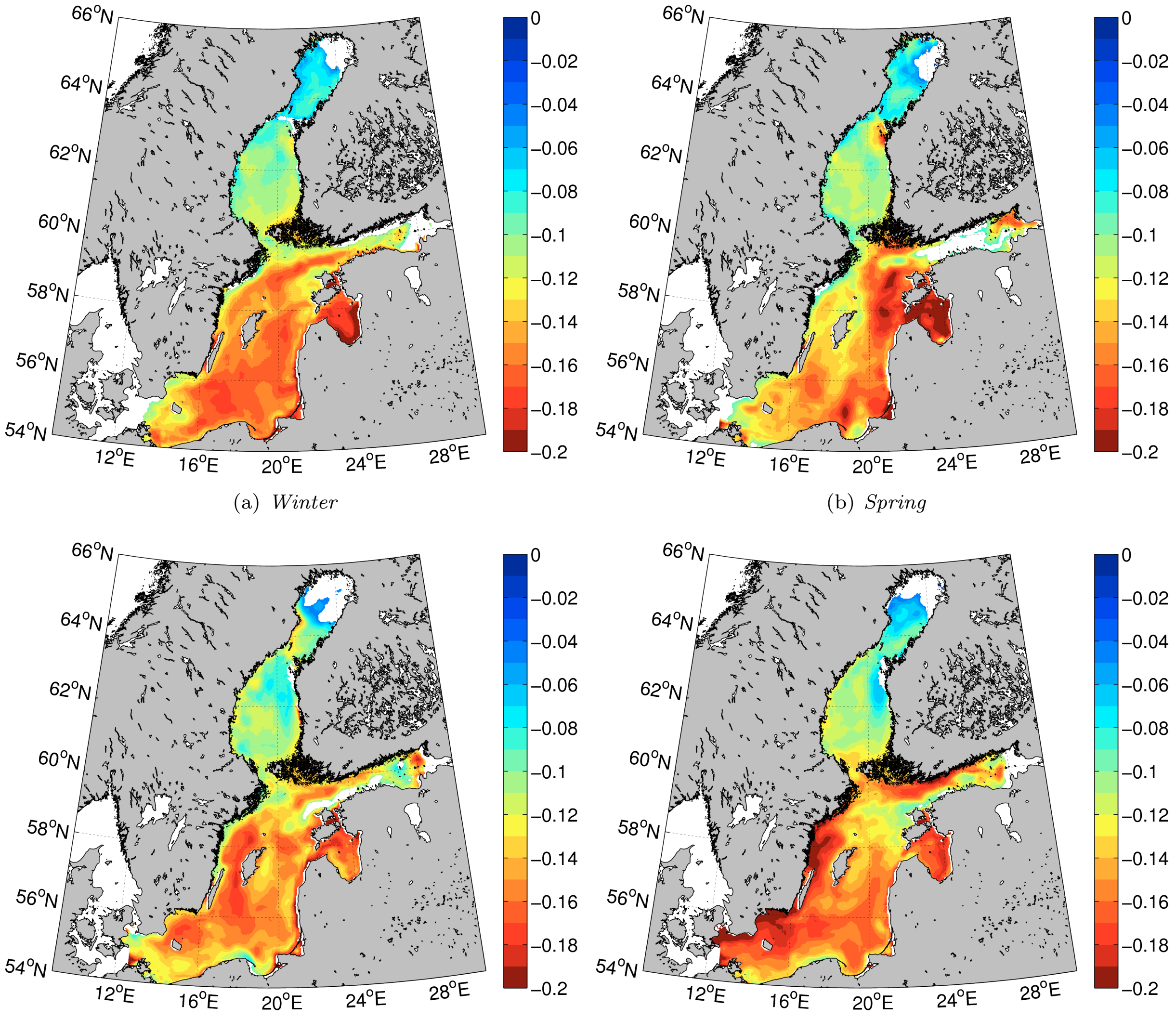
The mean halocline vertical salinity gradient has also quite large interannual variations in all the stations of Baltic proper. The gradient is larger in the southern parts of the Baltic proper and smaller in the northern parts. During stagnation period the mean vertical salinity gradient decreased about 0.05-0.07 g/kg m^{-1} in the Baltic Proper, while the decrease in the Bornholm Basin was even larger. The halocline salinity gradient increased in all the stations after the major salt water inflow in 1993 with the most pronounced increase in the Bornholm Basin.

5. Discussion

In order to qualitatively estimate the impact of possible forcing parameters to the mean Baltic Sea salinity and halocline depth, we calculate the correlation between the variable and forcing serie in all the grid points. The time-series were low-pass filtered with cut-off period 4-years and variables studied either the salinity in the surface (averaged over the top 15 m) or below the halocline (averaged from 65 m to the sea bottom) and the halocline depth. The forcing parameters considered were the accumulated total runoff, mean zonal wind and absolute wind speed for both the salinity and halocline depth and in addition the freshwater content and mean meridional wind for the halocline depth.

The monthly mean surface salinity in most of the areas is controlled by the accumulated river runoff (Fig. 16). The negative correlation has remarkably high values in the Baltic proper, while it is modest in the northernmost and easternmost areas of the Baltic Sea. In those areas we had larger correlation between the unfiltered time-series of surface salinity and accumulated runoff. The correlation of the mean below halocline salinity with the accumulated river runoff is the largest in the Bothnian Sea, while it is negligible in the Bornholm Basin. Lower values were found in the Stolpe channel (values up to -0.6) and Gdansk Bay (values up to -0.7), while high correlation (values over -0.8) were in the deep parts of Baltic Proper. In the Bothnian Bay and Gulf of Finland, the correlations were significant (-0.7 to -0.8).

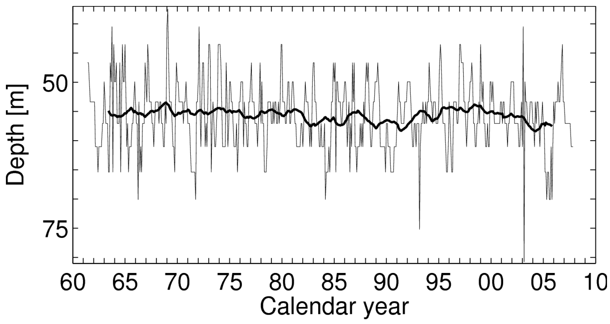
The correlation between the surface salinity and the mean zonal wind speed and the absolute wind speed is not significant (less than -0.4). The values exceeded -0.6 only in the easternmost parts of the Gulf of Finland, where increased westerly winds block the outflowing Neva river water and push them towards southern coast due to southward Ekman transport. The westerly winds in the Gulf of Finland produce downwelling on the southern and upwelling on the northern coast, which promotes the southward Ekman transport. The correlations between the unfiltered



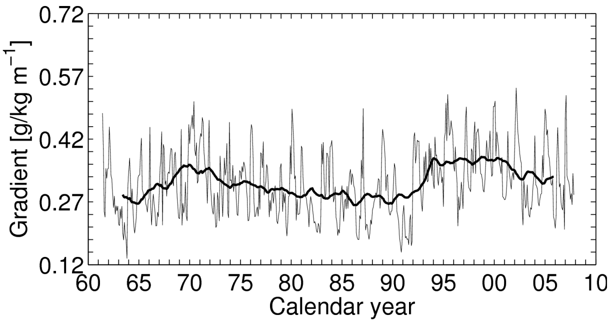
(a) *Winter* (b) *Spring*

(c) *Summer* (d) *Autumn*

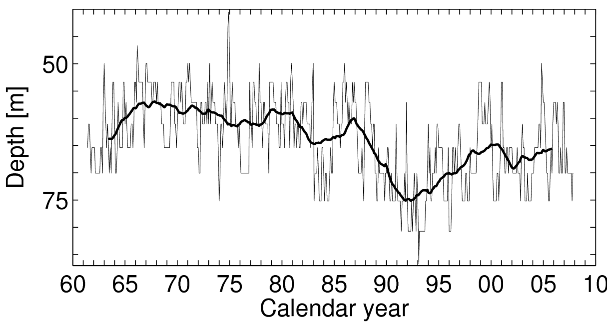
Figure 14. Statistically significant trend in the monthly mean salinity averaged over the top 15 m for different seasons during 1962-2007 ($p<0.05$). Units g/kg decade^{-1}.



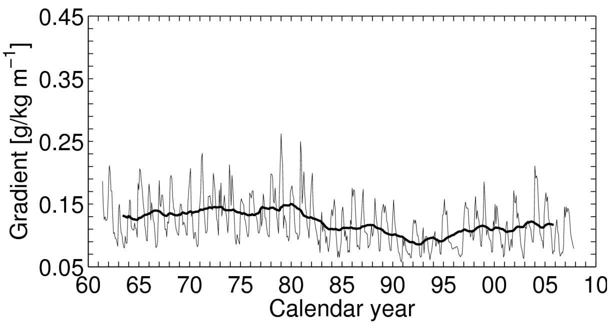
(a) *BY5, mean halocline depth*



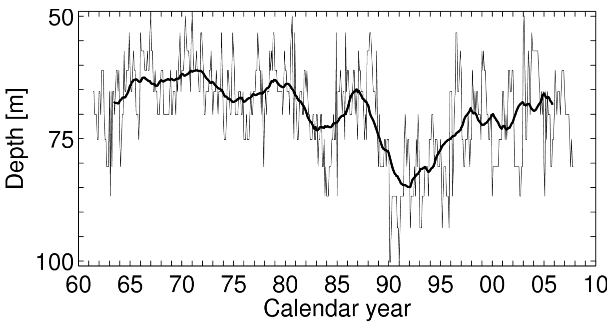
(b) *BY5, mean vertical salinity gradient*



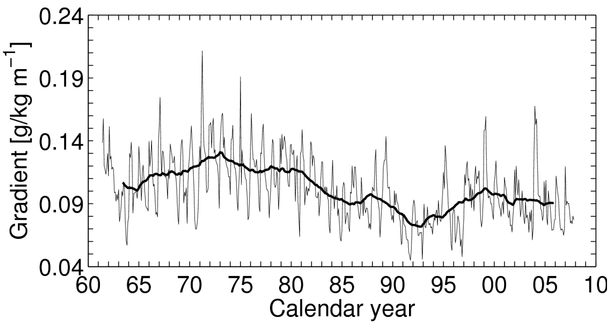
(c) *BY15, mean halocline depth*



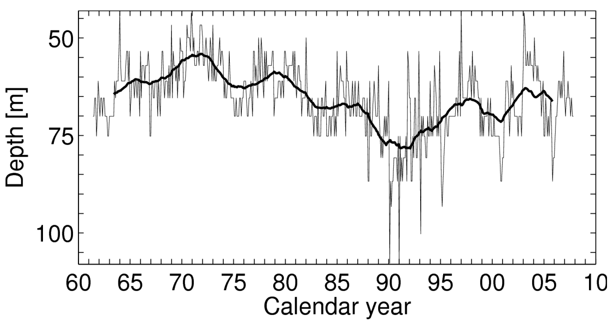
(d) *BY15, mean vertical salinity gradient*



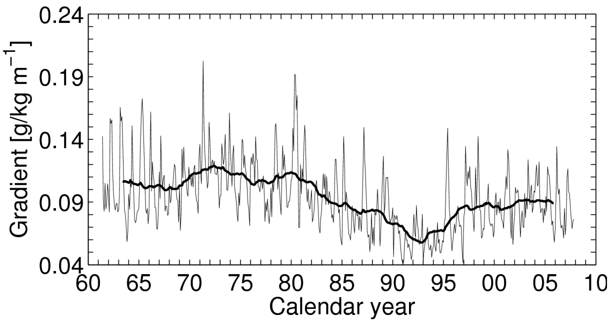
(e) *BY29, mean halocline depth*



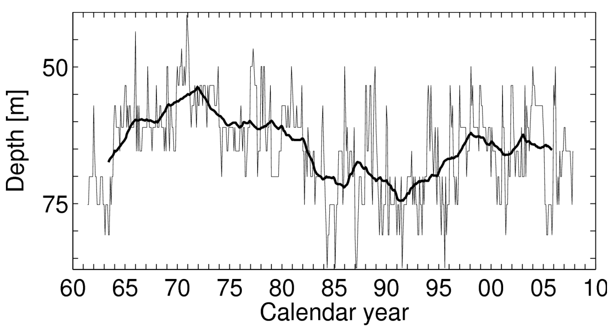
(f) *BY29, mean vertical salinity gradient*



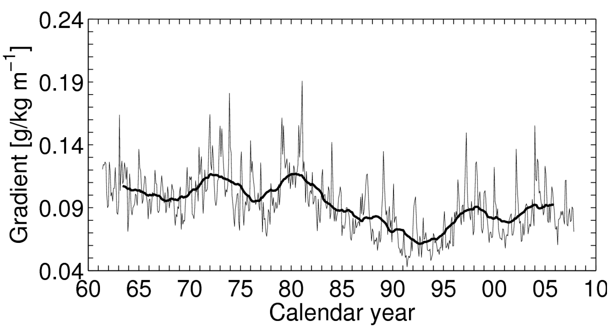
(g) *BY31, mean halocline depth*



(h) *BY31, mean vertical salinity gradient*



(i) *BY32, mean halocline depth*



(j) *BY32, mean vertical salinity gradient*

Figure 15. Time-series of (left) monthly mean halocline depth (thin line) or (right) mean halocline salinity vertical gradient in different monitoring stations with the 4-year running mean (bold line).

monthly mean salinity and monthly mean zonal windspeed were significant along the northern coast of the Gulf of Finland (positive values 0.4-0.6) indicating that more westerlies produce more upwelling on the northern coast of the Gulf of Finland.

The correlations between the mean zonal and absolute wind speed with the mean below halocline salinity are remarkably higher than the correlation bwetween the wind field and surface salinity. Especially high values are with the absolute wind speed in the Baltic Proper (values upto -0.8) and Gdansk Bay (values larger than -0.8). The below halocline salinity in the Gulf of Finland has larger correlation with the mean zonal wind speed, while the northern parts of Baltic Sea with the absolute wind speed. The impact of the westerlies to the Baltic Sea salinity was explained by *Meier and Kauker* [2003a]. The stronger correlation with the absolute wind speeds comapred with the mean zonal wind needs further investigation.

The correlation between the monthly mean halocline depth with the accumulated total runoff is the largest in the Bothnian Sea (Fig. 17a), while the correlation between the halocline depth and the total freshwater content is the largest in the western Gotland Basin (Fig. 17b), where most of the juvenile freshwater accumulates by August (see *Hordoir and Meier* [2010], their Fig. 4). The correlation with the freshwater content is significantly higher than the correlation with the total accumulated river runoff. In most areas of the Baltic proper the correlation is 0.6-1 for freshwater content and 0.2-0.8 for the accumulated total river runoff. The large difference between the correlation with the accumulated total river runoff and freshwater content is due to difference of the two parameters – the accumulated river runoff has time lag with most of the basins, while the total freshwater content in the location is showing immediate impact of the freshening of the water column to the mean halocline depth.

The monthly mean halocline depth is also very dependent on the monthly mean wind speed (Fig 18c). The correlation in the Baltic proper and Bothnian Bay is over 0.6, while in the Arkona Basin and the other parts of the Baltic Sea the correlation is smaller. The correlation of the halocline depth with the wind component is significant in case of the mean zonal wind speed, while the mean meriodional speed has very low effect. The correlation with the latter is the largest in the Bothnian Sea, where increasing southerly winds lift the halocline. The high correlation between the halocline depth and the absolute wind speed is due impact of vertical mixing to the mean halocline depth.

6. Summary

The salinity in the Baltic Sea has remarkable variations according to the high-resolution model simulations during the past 50 years. The trend in the mean salinity averaged over the top 15 m was the largest in the Gulf of Riga, but significant changes were also detected in the Baltic proper. The seasonal mean salinity averaged over the top 15 m has decreased in all parts of the Baltic proper during the winter, while the spring salinity in the eastern part and summer and autumn salinity in western and southern parts of Baltic proper.

The mean permanent halocline depth in the Baltic Sea has large interannual variations (more than 10m), while the seasonal variations exist only in specific locations most affected by the forcing. The seasonal cycle is pronounced in the Eastern Gotland Basin, where the wind forcing produces basinscale gyre and in the Northern Baltic proper, where the runoff effects dominate. We identified the shallow halocline period for the Baltic Sea during 1970-1975 and deep halocline period during 1990-1995, but the differences between the periods still need further investigation.

Surface salinity variations in different basins of the Baltic Sea depend most on the accumulated river runoff. The correlation in the Baltic proper exceed -0.9, while lower values were in the far-reaching parts of the Baltic Sea. The salinity below the halocline had large correlation with the absolute wind speed in the Baltic proper, but moderate correlation also with the mean zonal wind speed. The latter was significantly correlated with the salinity below the halocline in the Gulf of Finland, while it had no impact to the deep layer salinities in the northern parts of Baltic Sea.

The correlation between the monthly mean halocline depth with different forcing parameters is the strongest in case of wind speed and the total freshwater content as the values were larger than 0.6, reaching over 0.8 in the western Baltic proper. The effect of accumulated river runoff and monthly mean meridional wind in the Baltic proper was low, but strong correlation was found in the Bothnian Sea, where the runoff is the largest and the impact of runoff change to the water column salinity immediate.

Acknowledgments. This report is supported by the project ECOSUPPORT and Estonian Science Foundation (grant number 9278). Semjon Schimanke is sincerely acknowledged for the help with the LATEXscript. Anders Hglund for valuable comments.

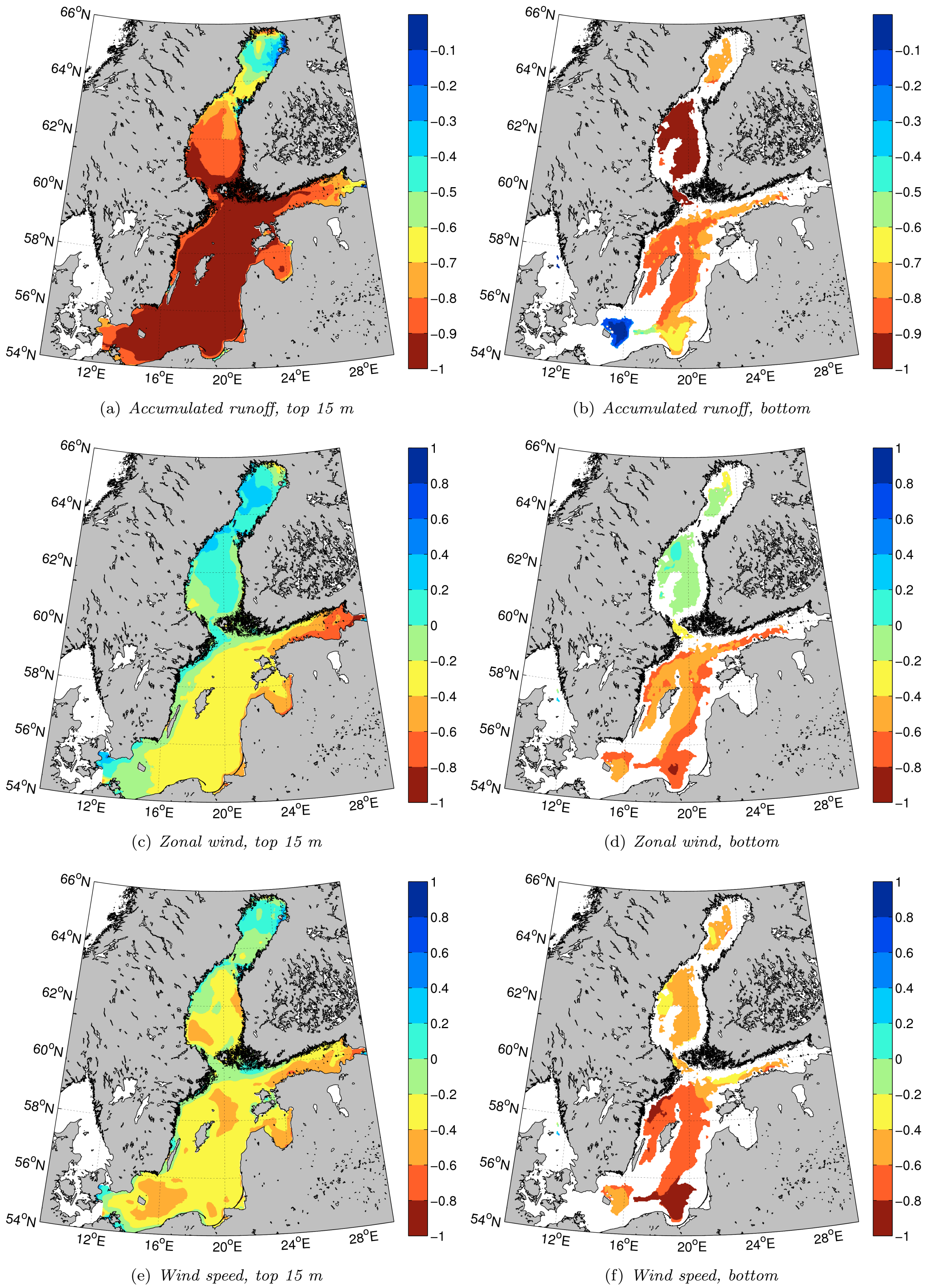
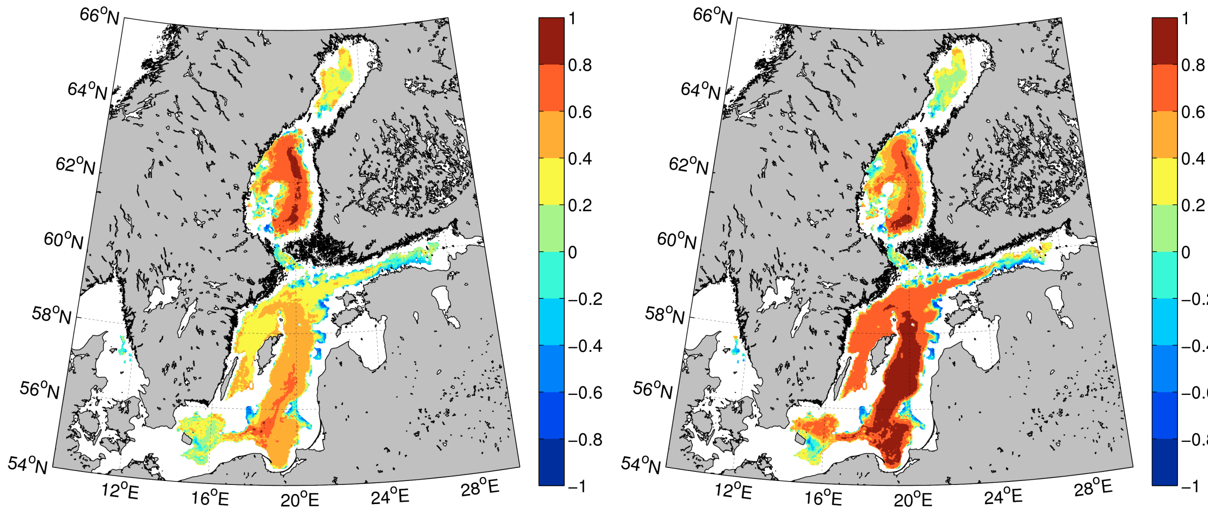


Figure 16. Spatial correlation of the mean salinity (left) averaged over top 15 m and (right) averaged from 65 m to the bottom with (a,b) the total accumulated runoff, (c,d) the mean zonal wind speed and (e,f) the mean windspeed.



(a) *Accumulated runoff* (b) *Freshwater content*

Figure 17. Spatial correlation of the mean halocline depth with the (a) total accumulated runoff to the Baltic Sea and (b) freshwater content.

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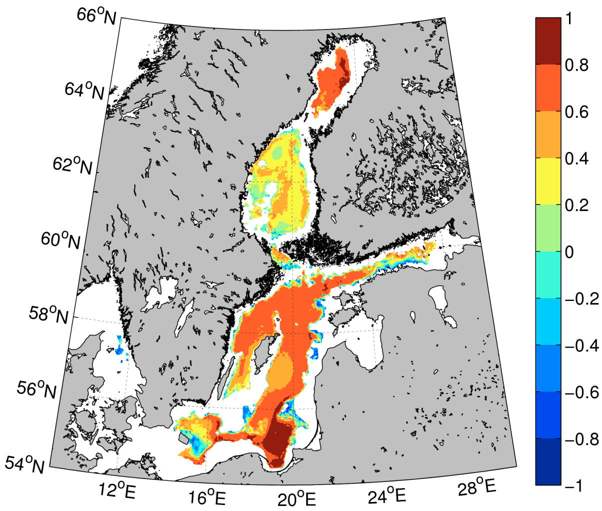
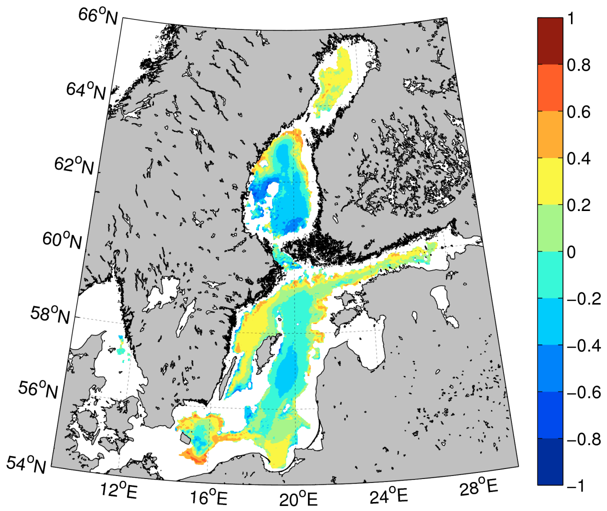
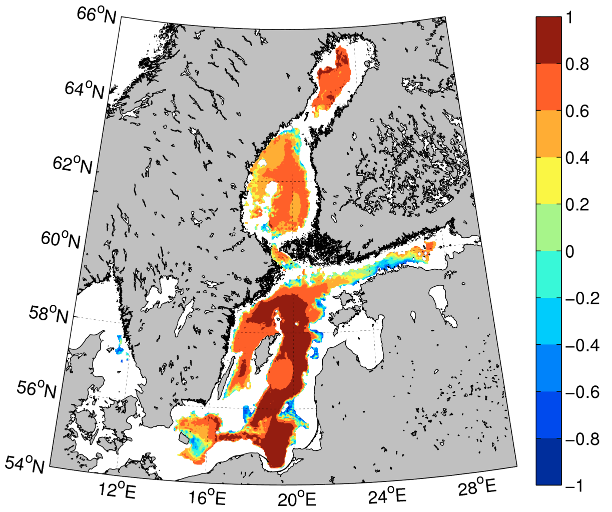


(a) *Zonal wind*



(b) *Meridional wind*



(c) *Wind speed*

Figure 18. Spatial correlation of the mean halocline depth with the monthly mean (a) zonal wind, (b) meridional wind and (c) absolute wind speed.

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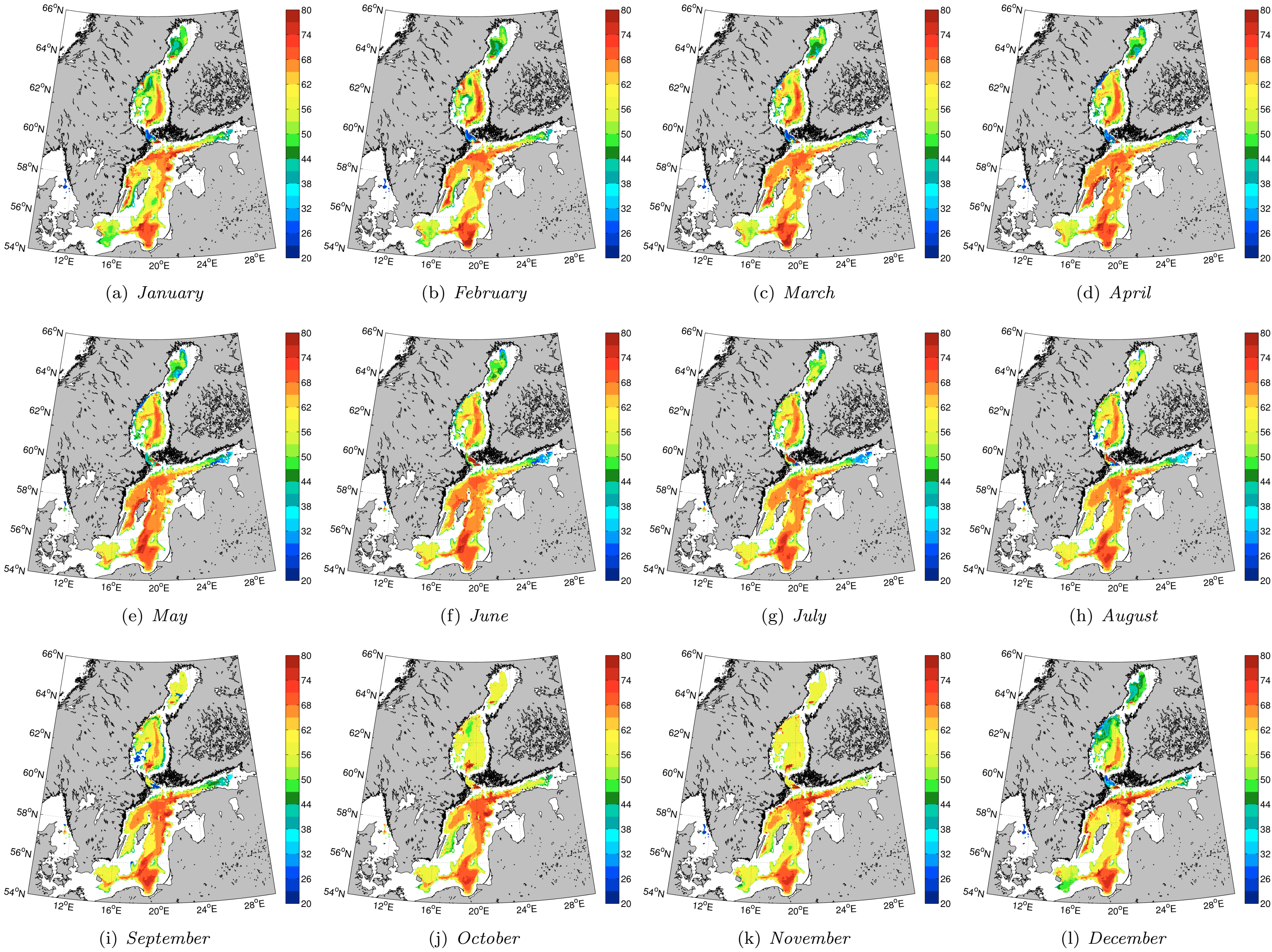
Appendix A: Seasonal variability

This section contains the annual cycle for halocline depth during climatologic period (1962-2004), period with low (1970-1975) and deep halocline depth (1990-1995) based on monthly means from January-December. We also show the seasonal cycle of mean halocline vertical salinity gradient for the same periods.



(a) *January* (b) *February* (c) *March* (d) *April*

(e) *May* (f) *June* (g) *July* (h) *August*

(i) *September* (j) *October* (k) *November* (l) *December*

Figure A1. The climatologic annual cycle of halocline depth in the Baltic Sea based on mean salinity over 1962-2004.

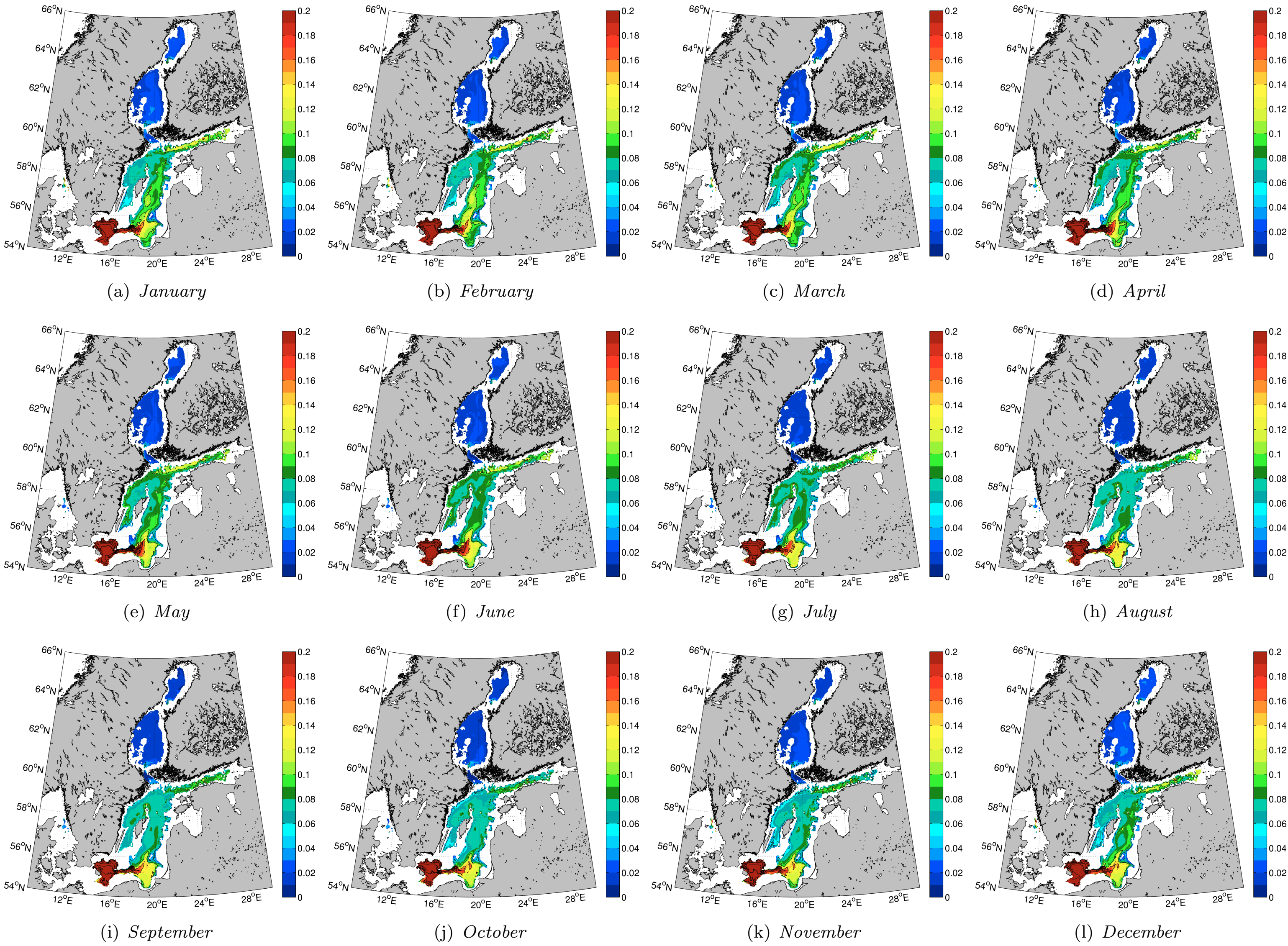
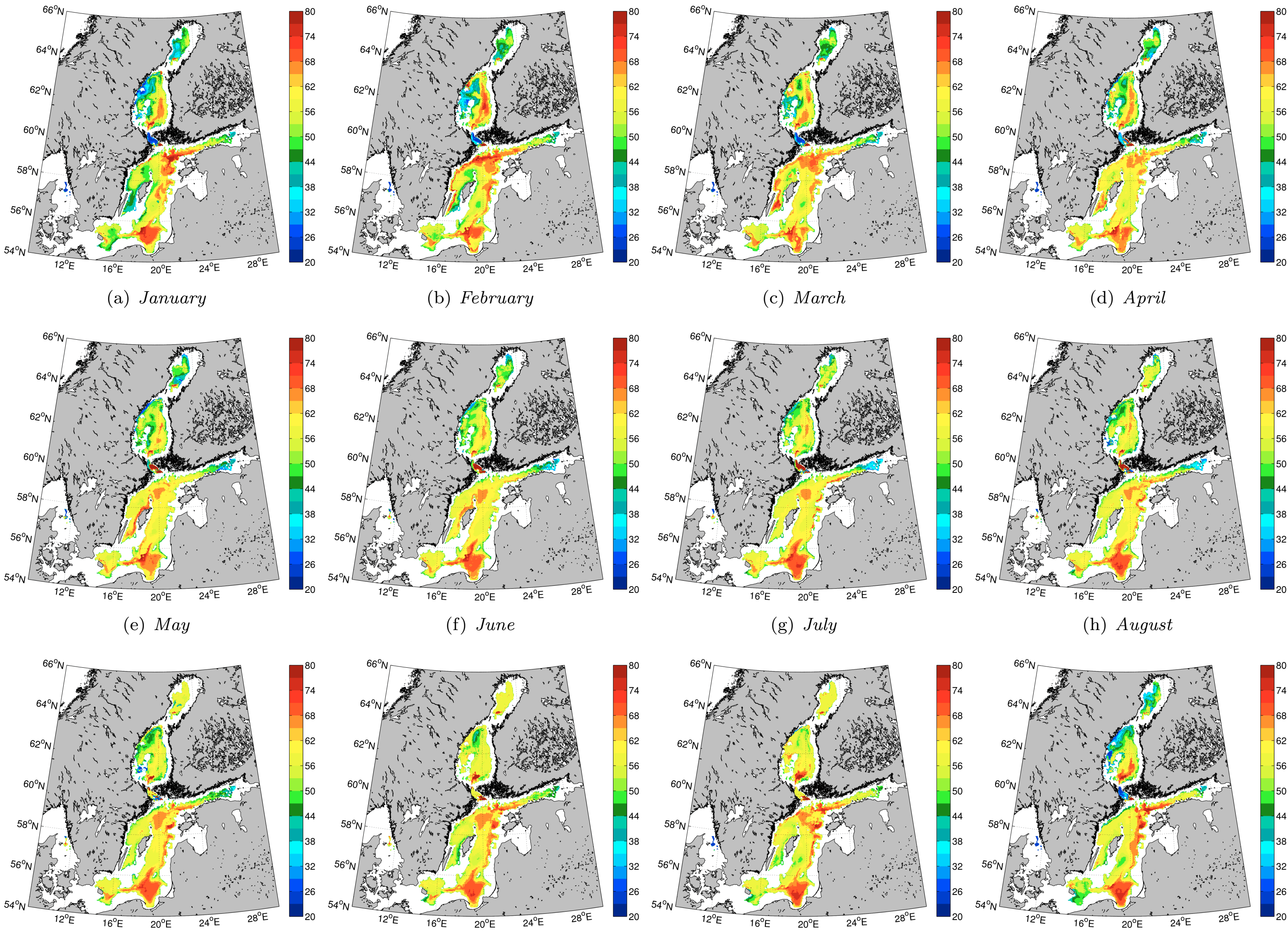


Figure A2. The climatologic annual cycle of salinity gradient in the Baltic Sea halocline based on mean salinity over 1962-2004.

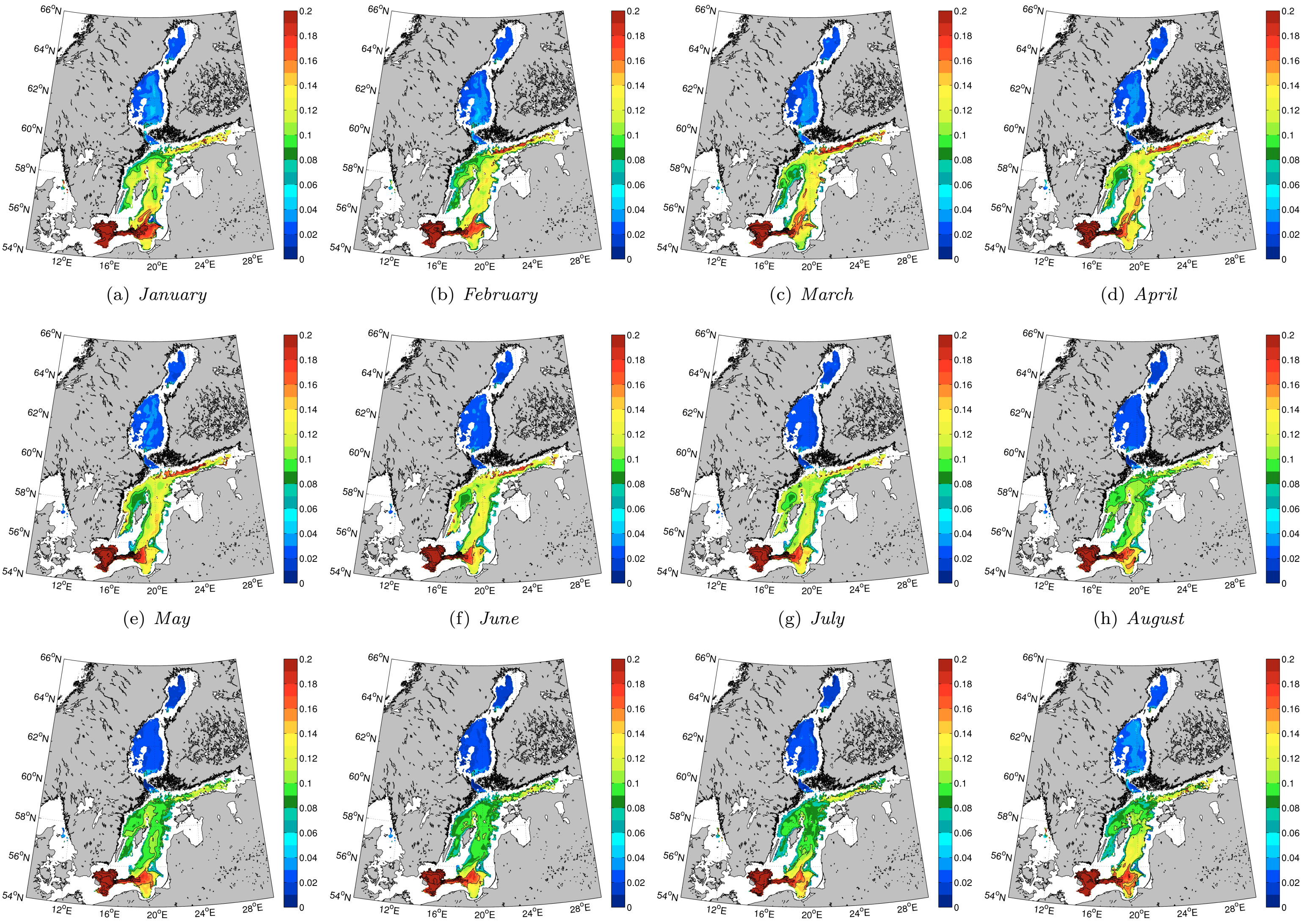


(a) *January* (b) *February* (c) *March* (d) *April*

(e) *May* (f) *June* (g) *July* (h) *August*

(i) *September* (j) *October* (k) *November* (l) *December*

Figure A3. The annual cycle of halocline depth in the Baltic Sea during the shallow halocline period in 1970-1975.

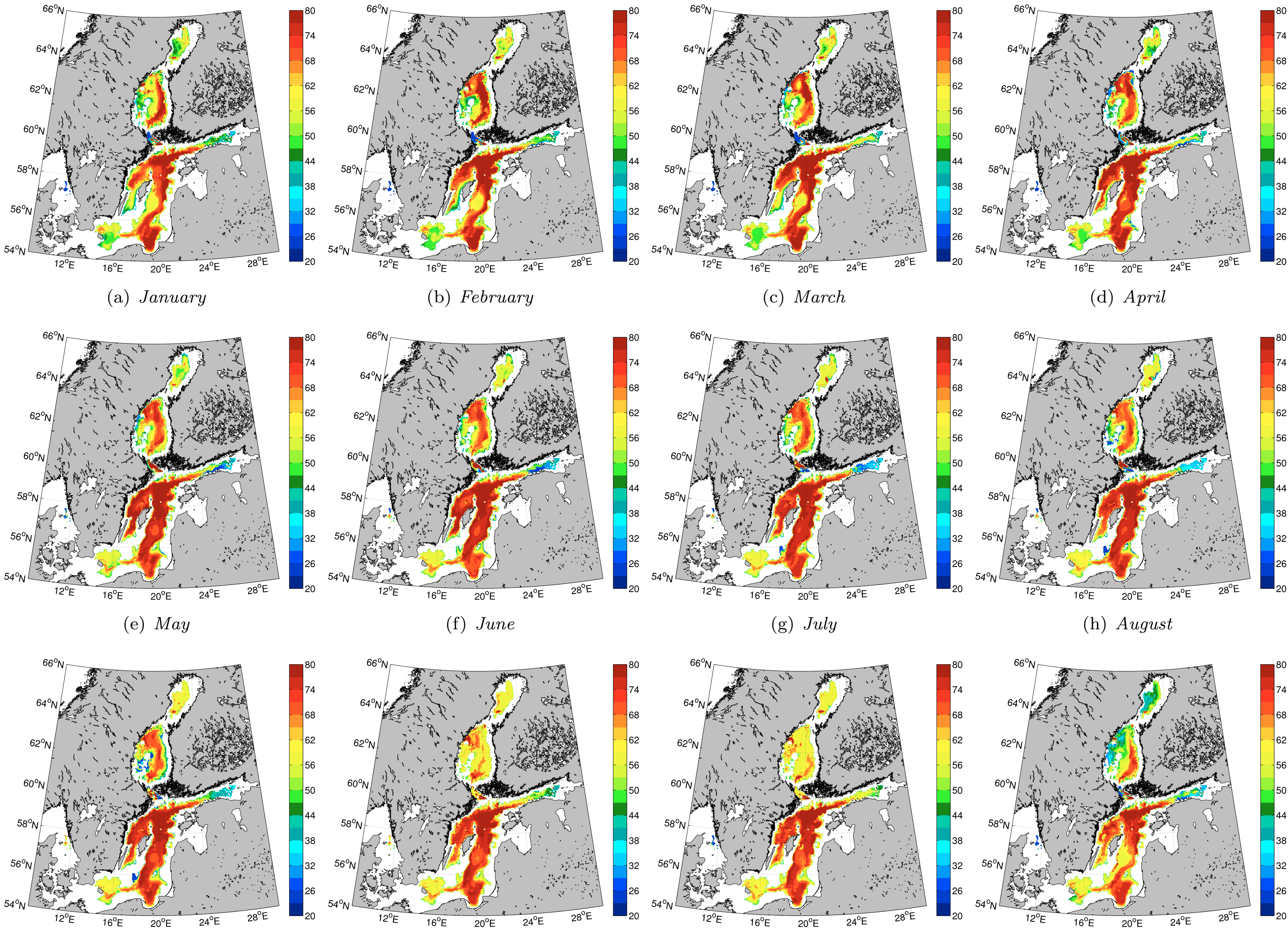


(a) *January* (b) *February* (c) *March* (d) *April*

(e) *May* (f) *June* (g) *July* (h) *August*

(i) *September* (j) *October* (k) *November* (l) *December*

Figure A4. The annual cycle of salinity gradient in the Baltic Sea halocline during the shallow halocline period in 1970-1975.



(a) *January* (b) *February* (c) *March* (d) *April*

(e) *May* (f) *June* (g) *July* (h) *August*

(i) *September* (j) *October* (k) *November* (l) *December*

Figure A5. The annual cycle of halocline depth in the Baltic Sea during the deep halocline period in 1990-1995.

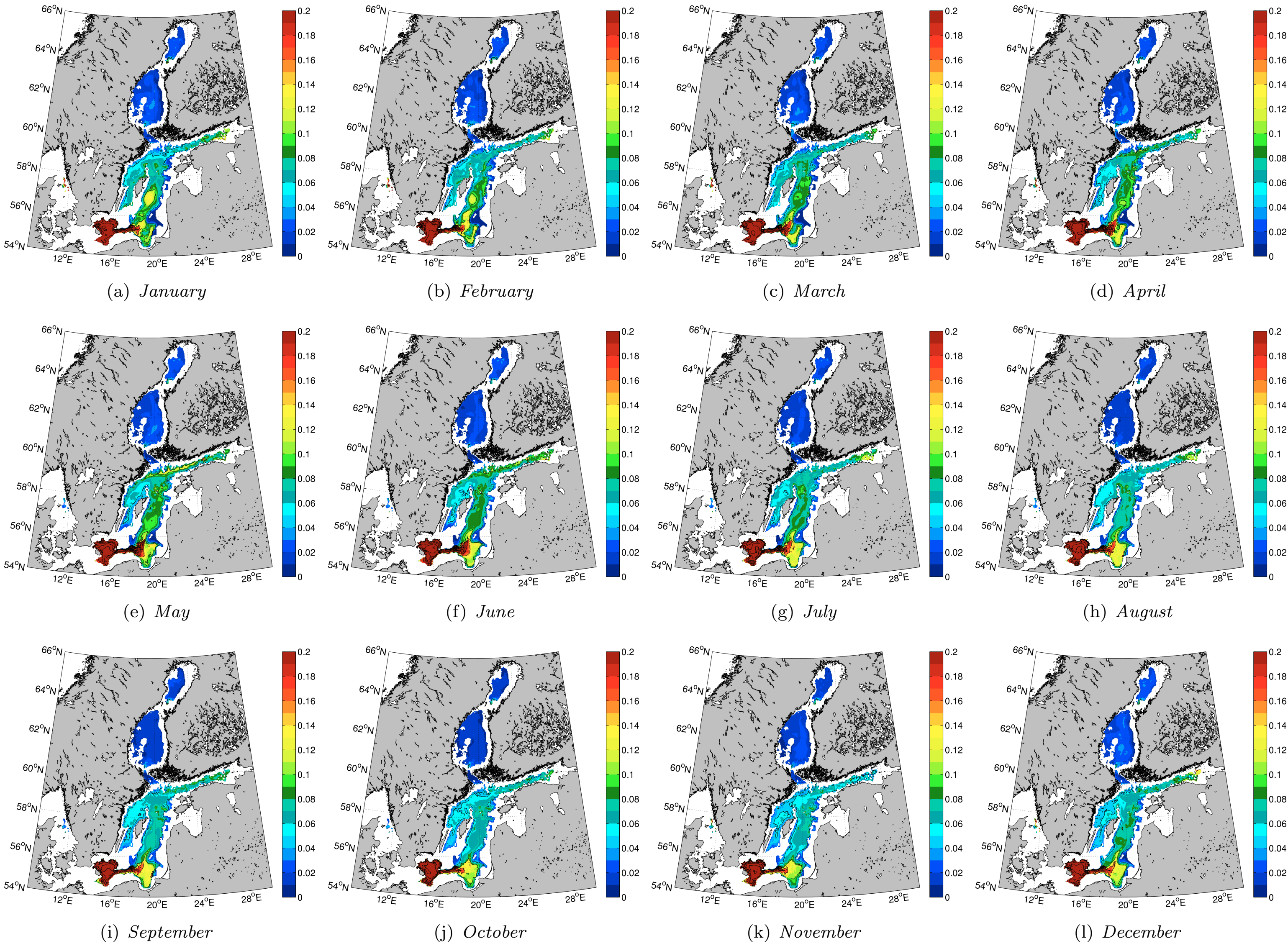
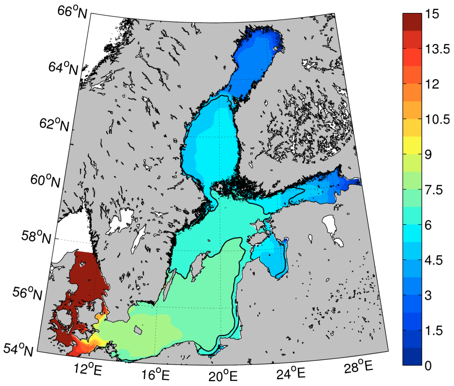


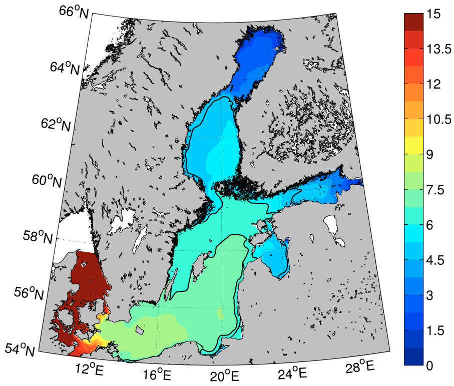
Figure A6. The annual cycle of salinity gradient in the Baltic Sea halocline during the deep halocline period in 1990-1995.

Appendix B: Interannual variability

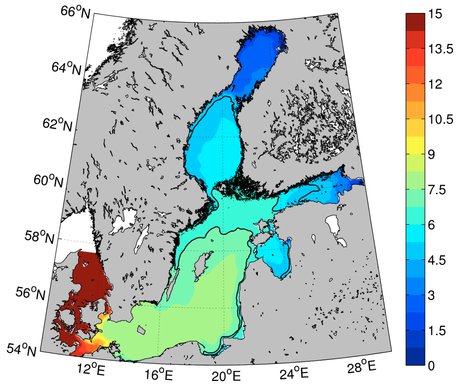
This section contains the interannual variability based on 5-year means of the monthly mean surface salinity (averaged over the top 15 m), monthly mean below halocline salinity (averaged from 65 m to the bottom) and the halocline depth.



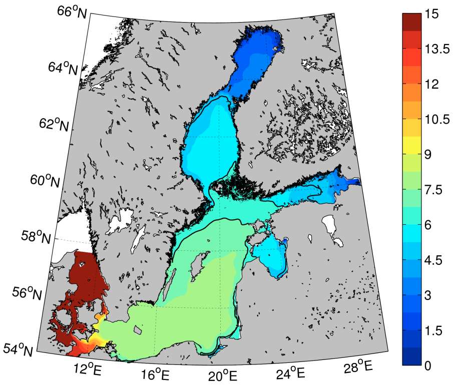
(a) *1961-1965*



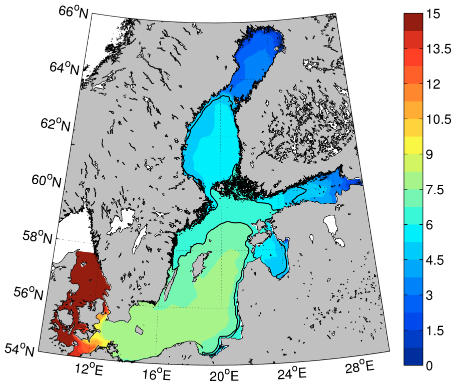
(b) *1966-1970*



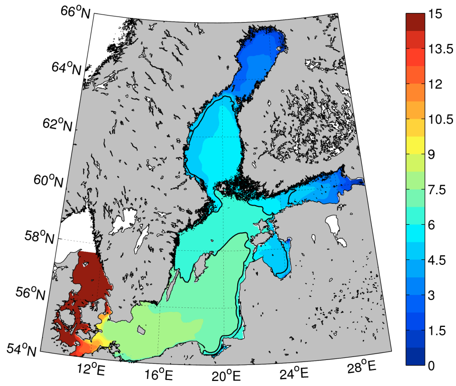
(c) *1971-1975*



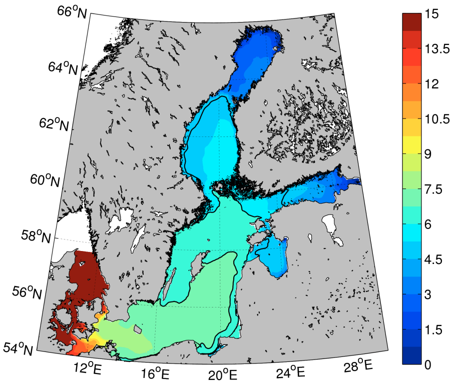
(d) *1976-1980*



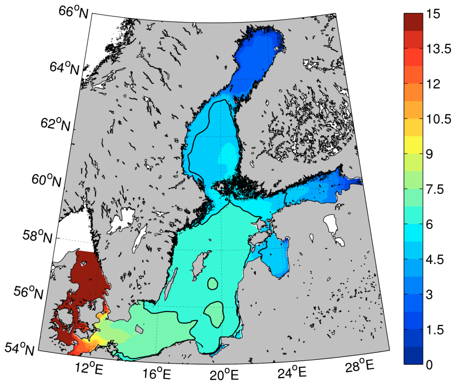
(e) *1981-1985*



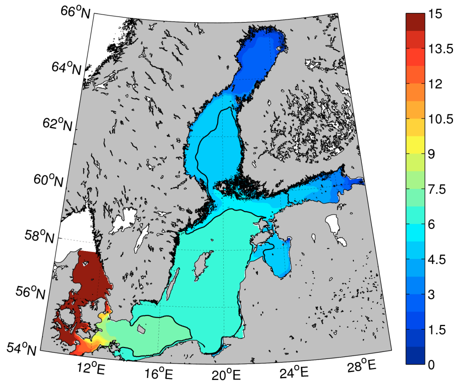
(f) *1986-1990*



(g) *1991-1995*

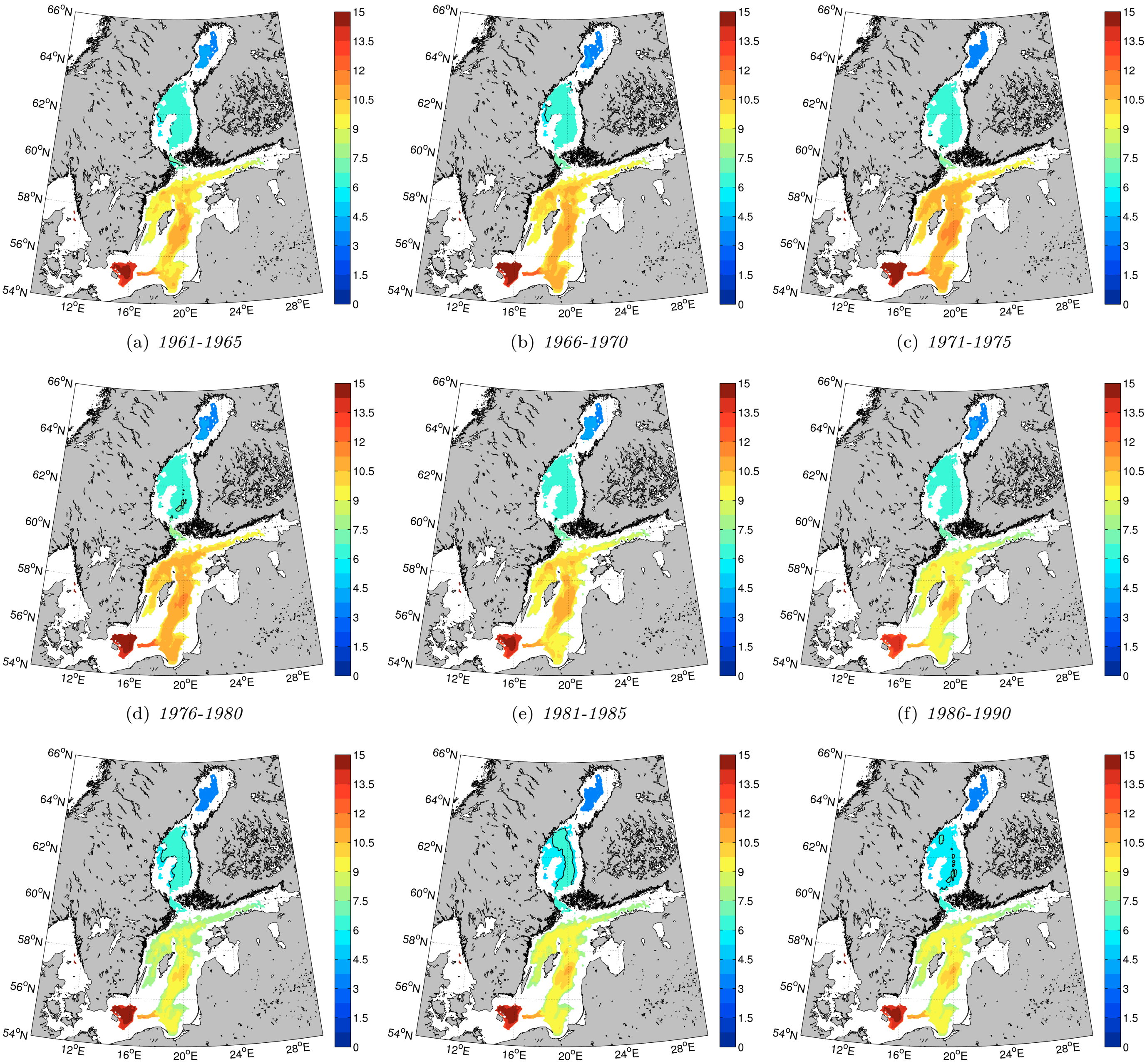


(h) *1996-2000*



(i) *2001-2005*

Figure B1. The 5-year mean salinity averaged over top 15 m for different periods. Units g/kg.



(a) *1961-1965*

(b) *1966-1970*

(c) *1971-1975*

(d) *1976-1980*

(e) *1981-1985*

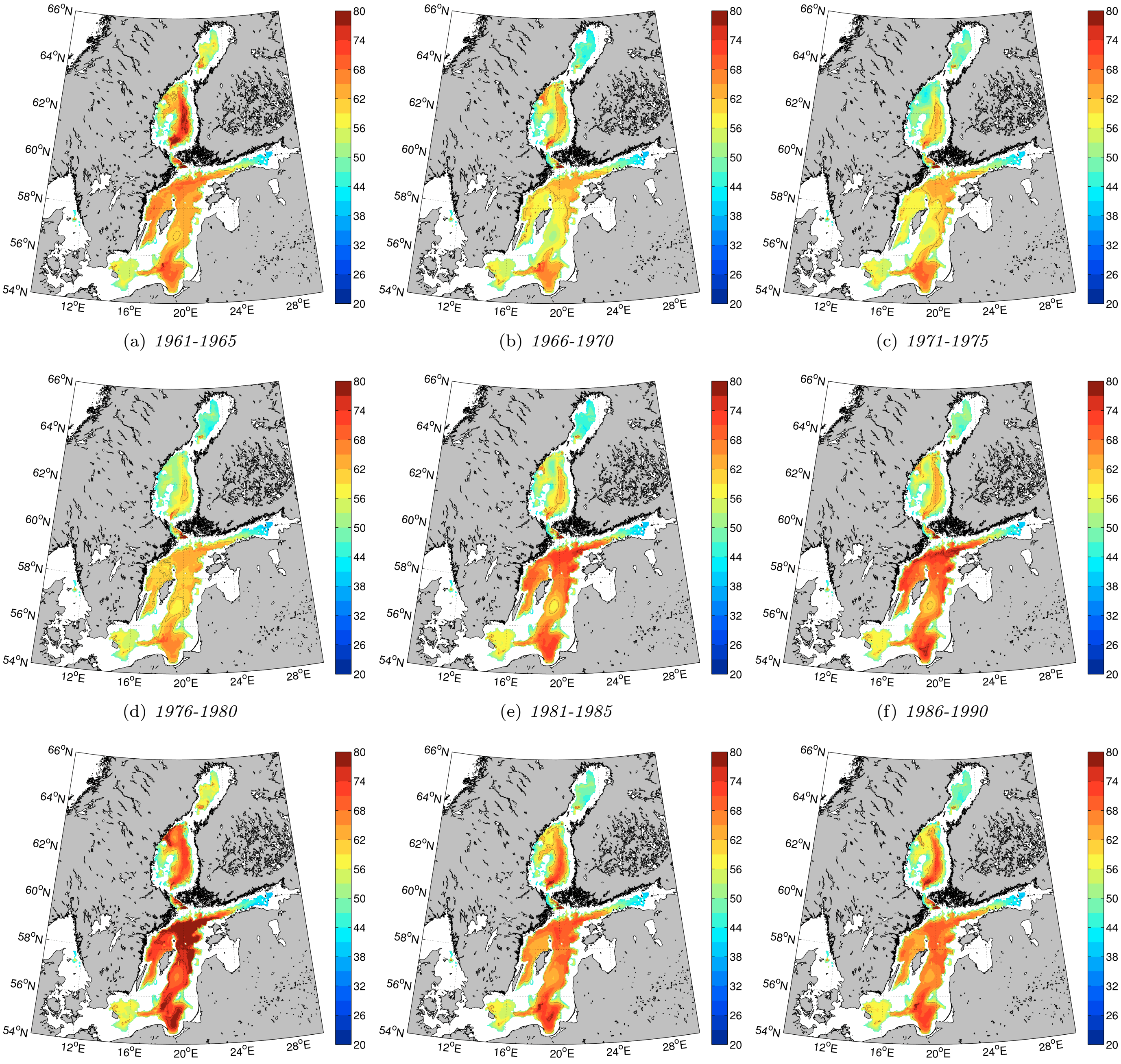
(f) *1986-1990*

(g) *1991-1995*

(h) *1996-2000*

(i) *2001-2005*

Figure B2. The 5-year mean salinity averaged from 65 m to the sea bottom for different periods. Units g/kg.



(a) *1961-1965* (b) *1966-1970* (c) *1971-1975*

(d) *1976-1980* (e) *1981-1985* (f) *1986-1990*

(g) *1991-1995* (h) *1996-2000* (i) *2001-2005*

Figure B3. The 5-year mean halocline depth for different periods. Units m.

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