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The influence of river runoff on deep water conditions of the Baltic Sea

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Abstract

The effect of variations in river runoff on abiotic environmental conditions in the deep water of semi-enclosed stratified sea areas in humid climatic zones in temperate latitudes was investigated using the Baltic Sea as an example. Runoff has an indirect effect on deep water conditions, where it acts through two mechanisms. First, in the shallow transition area, the inflowing highly saline water is transformed by mixing with the outflowing low saline Baltic water diluted by runoff. The transformed water which crosses the sills penetrates into the central basins, thereby additionally mixing with the ambient water along its path. Second, is the impact of runoff variations on the occurrence of major inflow events. Variations in the annual runoff might contribute to the strength of inflows. Reduced runoff increases the probability of inflow events. Since the mid-seventies, the frequency and intensity of major Baltic inflows has changed, only a few major events having occurred since then. Drastic changes in environmental conditions in the central Baltic deep water can be explained by increased zonal circulation linked with more intensive precipitation in the Baltic region and increased river runoff into the Baltic. There are signs that anthropogenic changes in runoff due to river regulation may be causing changes in the frequency of major inflows.

Introduction

The water exchange between the ocean and landlocked basins and seas in temperate latitudes is governed by topographic, meteorological and oceanographic factors. Where the water exchange is restricted by narrow channels and shallow sills, regular inflows of saline water make such sea areas brackish and lead to vertical haline stratification.

The Baltic Sea is such a semi-enclosed sea. Its narrow, shallow transition area consisting of the Kattegat and Belt Sea greatly restricts the water exchange with the North Sea, giving the water in the Baltic Sea a residence time of 25–35 years.

The Baltic Sea (Figure 1) has a drainage area, which is four times larger (Figure 1A; heavy line). Like other landlocked seas in humid climatic regions, the Baltic Sea has a positive water balance. Its mean annual fresh water surplus of 481 km^3 has nearly the same volume as the annual inflow of saline water from the North Sea (Helcom, 1986). The fresh water balance (river runoff [428 km^3] + precipitation [237 km^3] − evaporation [184 km^3]) is dominated by runoff because precipitation and evaporation are relatively well balanced. The annual runoff is about 2% of the Baltic Sea volume and would raise the Baltic sea level by about 1.1 m per year if the Baltic entrances were blocked.

The water body of the central Baltic is permanently stratified, consisting of an upper layer of brackish water with salinities of 6–8 PSU and a more saline deep water layer of 10–14 PSU. A strong halocline and thermocline at depths between 60 and 80 m prevents vertical circulation and, consequently, ventilation down to the bottom all year round. During spring, a thermocline develops at 25–30 m depth restricting additionally vertical exchange within the upper layer until late autumn. The horizontal deep water circulation is restricted by submarine sills, separating a series of subbasins.

The specific hydrographic–chemical conditions and the evolutional history of the Baltic Sea have given rise to a quite unusual aquatic biota consisting of relatively few marine and fresh water species. Due to the

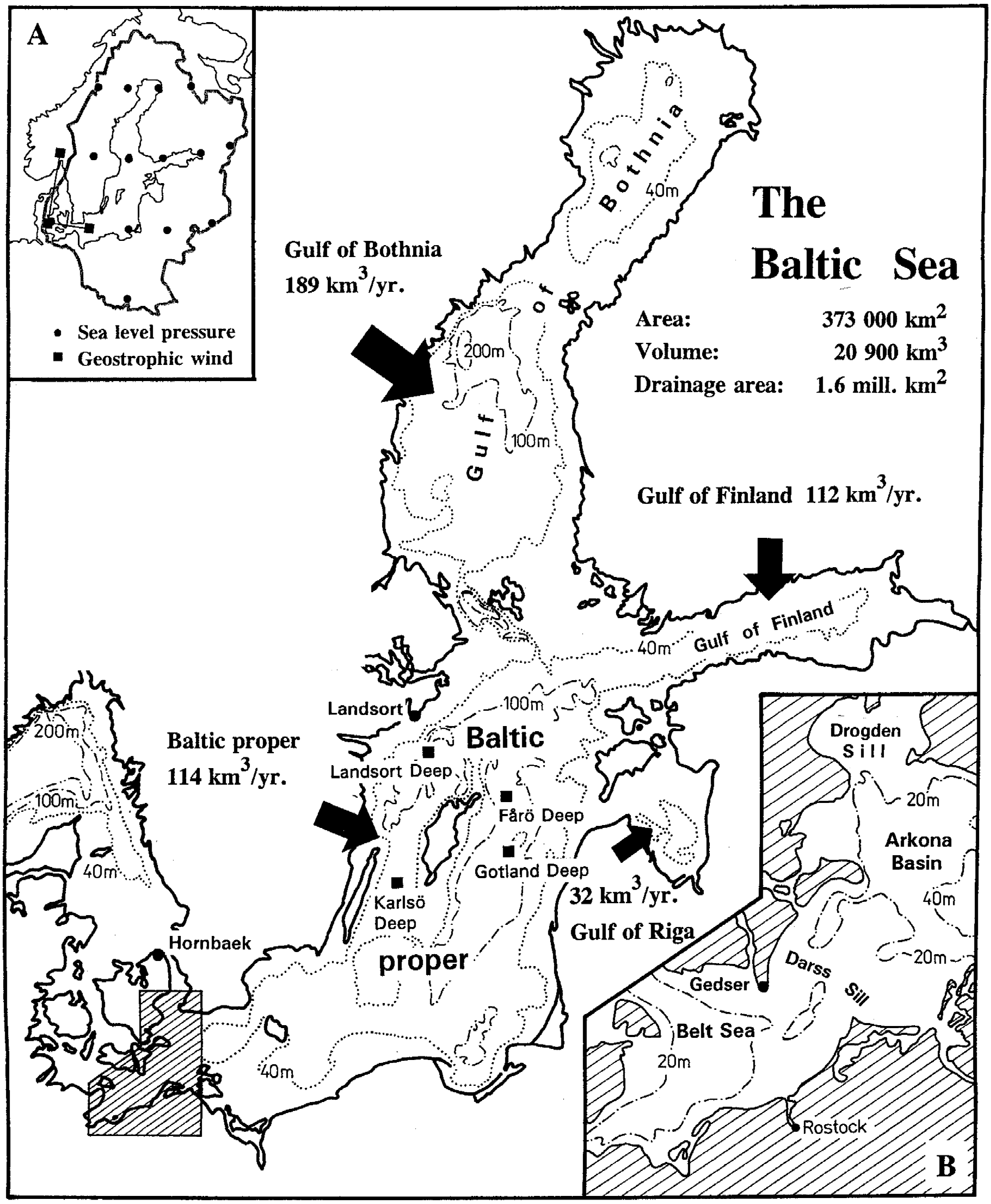

Figure 1. The Baltic Sea, its drainage area and the location of measurement stations. (Figures correspond to the Baltic Sea excluding Kattegat and Belt Sea). Arrows: mean annual contribution of river runoff to the Baltic Sea subbasins according to Bergström & Carlsson (1994).

long residence time and the ecological conditions, the Baltic Sea is very sensitive to any change in its environment. Variations in river runoff may trigger such changes.

Effects on abiotic environmental conditions in the Baltic Sea can be caused by variations in river runoff in two ways: In the surface water, they have a direct effect by lowering the salinity and mixing down to the thermocline (25–30 m) during summer and to the permanent halocline (60–80 m) during winter (cf. also Samuelsson, 1996).

The impact of runoff on the deep water conditions, however, can only be an indirect one. The deep water is influenced by inflows of saline water from the Kattegat and North Sea. The very frequent but small inflows (10–20 km^3) have little impact on the deep and bottom waters because their water will be incorporated in or flow just beneath the permanent halocline. Episodic inflows of larger volumes (100–250 km^3) of highly saline (17–25 PSU) and oxygenated water – termed major Baltic inflows (MBI) – represent the only mechanism by which the central Baltic deep water is renewed to a significant degree, and their incidence may be influenced by runoff. The water entering the sea during MBI is dense enough to replace the deep and bottom waters.

The impact of river runoff variations on the deep water of the central Baltic Sea is reviewed here by investigating the interaction between major inflows and runoff.The data sets used cover the period 1899–1993 and refer to the Baltic Sea itself (major inflows, salinity, oxygen, sea level), the drainage area (river runoff, precipitation) and the North Atlantic and Europe (sea level pressure). The basic data sets are time series for major Baltic inflows during the present century (Franck et al., 1987; Matthäus & Franck, 1992) and for river runoff to the Baltic Sea inside the entrance sills (Mikulski, 1982; Bergström & Carlsson, 1994).

Variations in abiotic environmental conditions in the Baltic deep water

Variations in environmental conditions in the deep water of the Baltic Sea are strongly influenced by inflows of saline and oxygenated water from the North Sea. Because such inflows are restricted by narrow channels and shallow sills (Darss Sill: 0.8 km^2 cross section, 18 m sill depth; Drogden Sill: 0.1 km^2 cross section, 7 m sill depth; see Figure 1B), the deep water in the central basins tends to stagnate for periods of several years. The consequences are decreasing salinity and oxygen depletion due to remineralization of organic material that has settled from the surface layers. This can completely consume the dissolved oxygen, thereby creating anoxic conditions and leading to the formation of considerable concentrations of hydrogen sulphide. The lack of oxygen leads to impoverishment and finally to the disappearance of the benthic community. Only major inflows are able to displace the stagnant (anoxic) deep water and significantly improve the living conditions.

A total of 96 major inflows has been identified during the past 100 years, the two world wars excluded (Figure 2). The amount of salt ($\geq$17 PSU) in kg penetrating into the Baltic Sea across the Darss and Drogden Sills divided by 10^{11} was used as indicator of the intensity of major events (cf. Fischer and Matthäus, 1996). All inflows have occurred between the end of August and the end of April. Therefore, we call the period from the middle of one year to the middle of the next the *inflow season*. The seasonal frequency distribution of major inflows (Figure 2, top right corner) shows that such events are most frequent between October and February (90%) and less common in August/September and in March/April. Major inflow events have never been recorded between May and mid-August.

Major inflows usually occur in clusters (17 cases; black boxes on the time axis in Figure 2), but some have been isolated events (six cases). A cluster comprises all inflows separated by intervals of less than one year. Most clusters had a duration of several years, the longest being recorded from 1948 to 1952 (12 events). Before the late seventies, the longest period without an inflow event was three years (1927/1930; 1956/1959). Between February 1983 and January 1993, however, 10 years passed without a major event.

During the first three quarters of the present century, major inflows were observed more or less regularly (Figure 2). Since the mid-seventies, their frequency and intensity changed, and only a few major events have occurred since then. Environmental conditions in the central Baltic deep water changed drastically during this period which culminated in the most significant and serious stagnation period ever observed in the Baltic Sea (Nehring & Matthäus, 1991; Franck & Matthäus, 1992). Moreover, the major inflow in January 1993 (Håkansson et al., 1993; Jakobsen, 1995; Matthäus & Lass, 1995) was only an isolated event, and since 1995 conditions in the central Baltic deep water have again stagnated (Nehring et al., 1995).

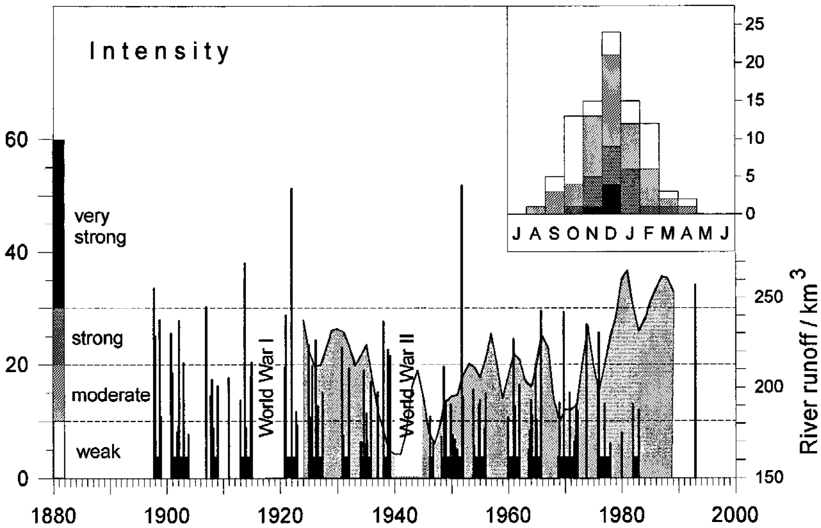

Figure 2. Major Baltic inflows (MBI) during the present century and their seasonal distribution (upper right) shown in terms of their strength (Matthäus & Franck, 1992; Fischer & Matthäus, 1996; updated) and low-pass filtered annual river runoff to the Baltic (inside the entrance sills) averaged from September to March (shaded). Black boxes on the time axis: MBI arranged in clusters.

Long-term variations in salinity in the central Baltic deep water show a rapid increase following major inflows and a subsequent decrease during the stagnation period. This pattern was observed more or less regularly during the present century until the 1970s. Since the mid-seventies, however, there has been a drastic decrease in salinity to such an extent that it has never been previously recorded (cf. Figure 6). This reduction in salinity correlates with the absence of major inflows (cf. Figure 2). The major event in January 1993 and smaller inflows during the 1993 to 1994 winter season terminated the stagnation period and resulted in a slight improvement, but salinities in the central Baltic deep water still failed to reach values comparable to those recorded prior to the mid-seventies.

Variations in the oxygen regime of the central Baltic deep water can be attributed only partly to the lack of major inflows. They are partly anthropogenic, being caused by inputs of inorganic nutrients from land-borne sources via river runoff and from atmospheric fallout via precipitation (Nehring & Matthäus, 1991; Matthäus, 1995; Helcom, 1996).

Figure 3 shows the variations in oxygen and hydrogen sulphide concentrations (the latter expressed as negative oxygen equivalents) from 1974 to 1996 at four stations located in the central Baltic (cf. Figure 1). Until the mid-seventies, a decrease in oxygen concentration was observed in the central Baltic deep water. After the last effective inflow in 1975–1976, however, the absence of advective inflows of saline and oxygen-rich water linked with the eutrophication of the Baltic surface water led to a decrease in the oxygen concentrations and to a drastic increase in hydrogen sulphide in the Gotland and Fårö Deeps, resulting in the highest H_2S concentrations ever measured in the Baltic Sea (Figure 3, panel G, F). In the western Gotland Basin, however, the decreasing salinity and stability of the water column caused the oxygen concentration to increase (Figure 3, panel L, K).

There can be no doubt that both the lack of major inflows and man-made nutrient inputs were jointly responsible for the oxygen depletion and the increase in hydrogen sulphide in the eastern Gotland Basin. It is not possible, however, to state how much of this variation can be ascribed to which cause.

Impact of river runoff on the Baltic deep water

The dynamics in the transition area strongly affect the central Baltic deep water. The basic factors influencing the water body in the Belt Sea are known from field investigations (e.g. Wyrtki, 1953, 1954; Jacobsen, 1980; Lass et al., 1987) and model computations (e.g. Stigebrandt, 1983; Lass, 1988; Sayin & Krauss, 1996; Gustafsson, 1998). Multiple regression analysis has identified the sea level pressure field over the Baltic region and the wind field over the transition area in close connection with precipitation in the drainage area and

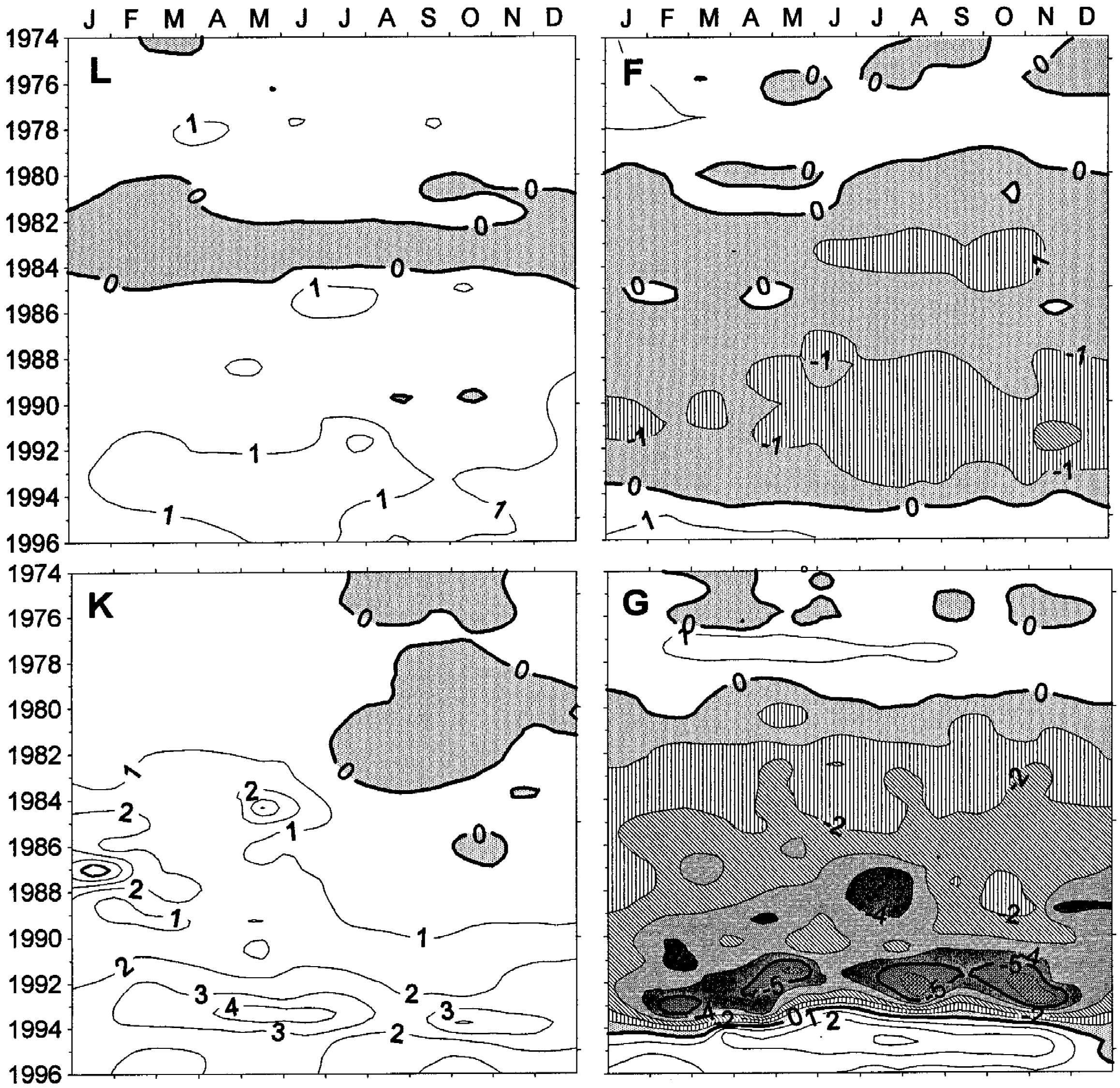

Figure 3. Variations in oxygen (>0) and hydrogen sulphide concentrations (<0, shaded) in the deep water of Landsort (L; 400 m depth), Karlsö (K; 100 m), Fårö (F; 150 m) and Gotland Deeps (G; 200 m) between 1974 and 1996 (for location of stations see Figure 1).

river runoff into the Baltic as the main variables influencing salinity at the Darss Sill (Schinke & Matthäus, 1998).

The well-documented runoff from the drainage area accounts for the main part of the annual fresh water surplus of the Baltic. How strong is the contribution of river runoff to the deep water conditions?

The runoff can influence the deep water in two ways. On average, there is an outflow of low saline water diluted by runoff in the surface layer and an inflow of higher saline water in the deep layer of the transition area. The entrainment of low saline outflowing water into the inflowing highly saline water is the predominant mixing process in the shallow area and presents a feedback mechanism for variations in runoff. Kõuts & Omstedt (1993) calculated that this entrainment adds even 79% to the deep water inflow in the Belt Sea and the Sound and still 53% in the Arkona Basin. The impact of runoff variations on the salinity conditions in the transition area can also be shown by model simulations (Lehmann, 1998). Kullenberg (1977) showed that the mixing in the Belt Sea has a considerable influence on salinity and oxygen conditions in the central Baltic deep water and is decisive for the depth to which the inflowing water can penetrate. Propagating from the sills into the central Baltic, the water is further diluted along its path by the entrainment of surrounding less saline water, and is finally incorporated in or just beneath the halocline.

During major Baltic inflows, the water body in the shallow transition area is transformed by strong mixing of the inflowing highly saline water masses with the outflowing low saline Baltic water. Owing to its higher density, the transformed water moves more rapidly into the central basins and descends into those layers between the permanent halocline and bottom that have a similar density. The mean distribution of the inflowing water entering the different layers of the central Baltic has been calculated by Stigebrandt (1987) by mathematical models.

The other way is that runoff variations directly affect the frequency and intensity of major inflow events. Reduced runoff seems to encourage inflow events by both helping to reduce the Baltic sea level and intensifying the deep current into the Baltic.

Impact of runoff variations on the occurrence of major Baltic inflows (MBI)

Variations in river runoff can be caused by variations in atmospheric processes (precipitation, evaporation), changes in the cryosphere (variations in the amount of accumulated snow and ice), variations in biological processes (growth of plants) and human activity (river regulation, ground sealing, agriculture and forestry). Runoff variations seem to play a more important role in salt transport into the Baltic than hitherto supposed, especially with regard to the occurrence or absence of major inflows. Model calculations by Gustafsson (1998) have already indicated that a decreased freshwater supply to the Baltic seems to result in a substantial increase in the magnitude of major inflows.

Comparison of inflow seasons with and without major Baltic inflows (MBI) has enabled us to identify significant differences between the kind of seasons (Figure 4). Our investigations show that river runoff is higher for nearly the whole inflow season without MBI and that the difference is highly significant for most months (Figure 4D). Precipitation in the northern part of the drainage area also shows distinct differences but significant only in August, October and – not relevant to MBI – April (Figure 4C). Similar results are valid for the southern part but this part contributes only 1/3 of the total runoff.

Rough estimations of mean precipitation, runoff and evaporation values for the drainage area averaged over all inflow seasons from 1922/1923 to 1987/1988 show that mean annual precipitation, on average, is 49 km^3 higher during inflow seasons without MBI than in seasons with MBI. Our estimations show that about 1/3 of the additional runoff (71 km^3) during seasons without MBI is due to increased precipitation and about 2/3 to reduced evaporation (cf. Schinke & Matthäus, 1998). It should be noted, however, that our considerations are based on the equation precipitation = runoff + evaporation, i.e. no other processes were considered. Furthermore, we assume that there no changes occurred in the amount of stored water.

During seasons without MBI, runoff and, consequently, net outflow is higher by a factor 1.2 to 1.3 between September and March than in seasons with MBI. There is no doubt that this increase in net outflow and, consequently, in mean outflow speed modifies the hydrographic conditions in the transition area.

On average, the higher atmospheric cyclonic activity from summer to autumn in seasons without MBI (cf. Figure 4A) leads to salinity decrease in the inflowing bottom water and hampers outflow from the Baltic. For this reason, the Baltic sea level between August and December is higher during seasons without MBI (Figure 4B) owing to the higher runoff and, partly, the lower air pressure. Both the sea level and the sea level difference between seasons with and without MBI start, on average, to sink from December onward. However, the general higher river runoff during seasons without MBI (cf. Figure 4D) causes stronger outflow and counteracts major inflows.

A comparison of the rankings of river runoff (in ascending order) with the number of major events per season confirms the close link between river runoff and the occurrence of MBI. Eight of the strongest major events during the period 1921/1922–1992/1993 occurred during the 15 seasons with the lowest runoff (cf. also Schinke & Matthäus, 1998).

The annual runoff distribution has changed in the course of the present century due to river regulations (Ehlin & Zachrisson, 1974; Hupfer et al., 1983; Bergström & Carlsson, 1994; Carlsson & Sanner, 1994). The annual freshwater outflow from the Baltic across the sills seems to be out of phase with the mean annual variations in its supply to the Baltic Sea (Rydberg, 1987; Gustafsson, 1998).

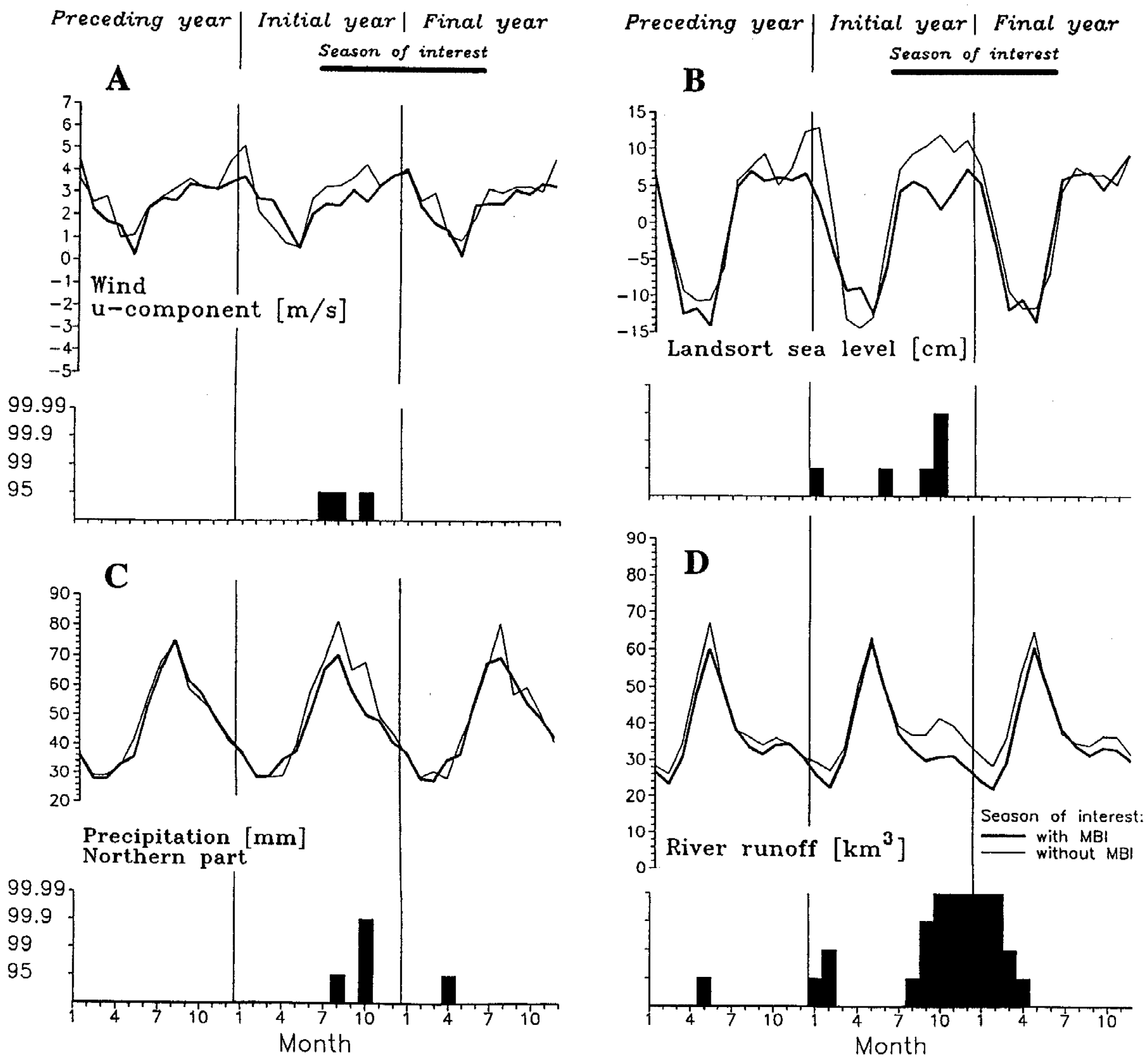

Figure 4. Mean annual variations of eastward component of the geostrophic wind (A), Baltic sea level at Landsort (B), precipitation in the northern part of the drainage area (C) and runoff (D) during a three-year period averaged over seasons with (heavy line) and without (thin line) major Baltic inflows (MBI) and the monthly significance levels of the differences (at the bottom of each graph).

As to runoff redistribution, mean runoff is not affected by river regulation in September and October, but gives rise to unfavourable conditions for the occurrence of MBI between November and April due to increased runoff. Therefore, runoff redistribution must be regarded as a possible cause for the absence of MBI.

Decrease in frequency and intensity of major Baltic inflows

The causes for the decrease in frequency and intensity of major events and the complete lack of MBI in the 1980s (cf. Figure 2) are discussed differently. Investigations have shown that major inflows are caused mainly by relatively long-lasting strong westwinds between the central North Atlantic and eastern Europe with only small fluctuations in wind direction over the transition area (Matthäus & Schinke, 1994). A preceding easterly wind period mainly due to high pressure over Scandinavia causing below-normal Baltic sea level is a characteristic phenomenon of major inflows (Lass & Matthäus, 1996). From this it may be assumed that a weakening of the zonal circulation during winter caused the lower frequencies and intensities of major events observed since the mid-seventies.

Long-term variations in the eastward component of the geostrophic wind and in the Baltic sea level,

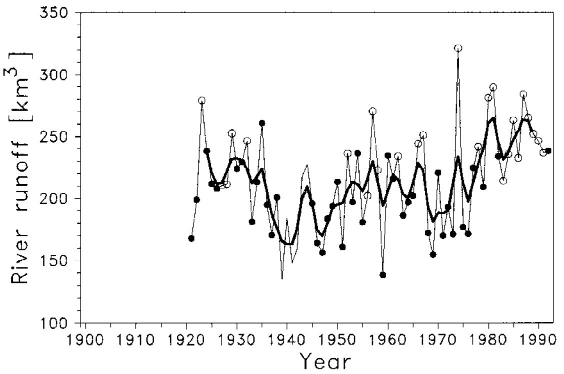

Figure 5. Annual river runoff to the Baltic (inside the entrance sills) averaged from September to March (heavy line: low-pass filtered values using cut-off period of 6 years). Filled circles: seasons with MBI; open circles: seasons without MBI.

however, have shown a mean increasing trend since the early 1970s, whereas the sea level pressure has slightly decreased (cf. Schinke, 1996). Compared with the total period, the Baltic sea level has mainly been distinctly above-normal during the last decade showing extreme high monthly means in 1989 and 1990 (cf. Ekman, 1996). This corresponds to a strengthening of the zonal circulation. Obviously, the decrease in major inflows is a more complex phenomenon. Our results suggest that the remarkably high river runoff during the last decades could be an essential cause. Figure 5 shows the variation of river runoff to the Baltic since 1921. MBI happen mainly during seasons characterized by lower runoff. Seasons identified by higher runoff have generally no MBI. River runoff has shown a characteristic increase since the early seventies. This is the only variable continuously showing significant differences throughout the whole period from August to April during inflow seasons without MBI compared to those with MBI (cf. Figure 4D). Runoff into the Baltic was abnormally high in the 1980s and 1990s, especially that to the Gulfs of Bothnia and Finland, which accounts on average for about 63% of the total runoff (Bergström & Carlsson, 1994; see also Figure 1). Inflow seasons with higher runoff (Figure 4D) depending on higher precipitation (Figure 4C) correlate with persistent westerly winds in late summer and autumn (Figure 4A) which results in an above-normal Baltic sea level (Figure 4B) by impediment of outflow from the Baltic and reduces the intensity of MBI or completely prevents such events.

The available data show that there was at least one MBI during each of the 29 seasons with the lowest river runoff rankings. Not any season from the recent period 1980/81–1992/93 is among them. Only one MBI was recorded during the 16 seasons with the highest river runoff, and that was a moderate one. This range includes seven seasons of the period 1980/81–1992/93.

The occurrence of MBI in clusters (cf. Figure 2) is a further hint that runoff (which is characterized by relatively low variability compared with synoptic processes) plays an important role in this process.

The decade 1981/1990 was the wettest period since 1920 (Bergström & Carlsson, 1994). Runoff was at a similar level during the decade 1921/1930 and above-normal runoff was also observed between the mid-fifties and the sixties (cf. Figure 5). The wet period 1980 to mid-1990s could be shown in precipitation and evaporation rates, too, estimated directly over the Baltic Sea (Omstedt et al., 1997; Isemer & Lindau, 1998). These periods correlated with periods of low frequency or absence of MBI (cf. Figure 2).

Bergström & Carlsson (1994) found that the increase in runoff during the 1980s was mainly due to increasing runoff from September to May. The increase in winter runoff (December–February) is common to all Baltic basins. It is partly an effect of the mainly mild winters since the end of the 1970s but, in the Gulf of Bothnia, also caused by hydroelectric power production. Apart from the effect of the redistribution of the runoff caused by river regulation, the increased atmospheric zonal circulation may transport wet air masses from the North Atlantic to Europe more frequently, resulting in intensified precipitation, lower evaporation and increased runoff (cf. also Hupfer et al., 1983).

Samuelsson (1996) discussed the salinity decrease in the Baltic during the 1980s in terms of runoff, the estimated salt water inflow and the estimated mixing rates. She assumes that the freshwater supply dilutes the mixed surface layer and causes a greater outflow from the Baltic. Inflows of saline water are thereby partly impeded (cf. also Gustafsson, 1998). However, there is a phase lag between the variations in runoff and salinity. Figure 6 shows salinity changes in the central Baltic deep water at four characteristic stations (cf. Figure 1) compared with the variation in river runoff to the Baltic Sea. The higher the runoff the lower the salinity, but the salinity variations are delayed by about 6 years (cf. also Launiainen & Vihma, 1990).

Concluding remarks

Variations in river runoff seem to play an important

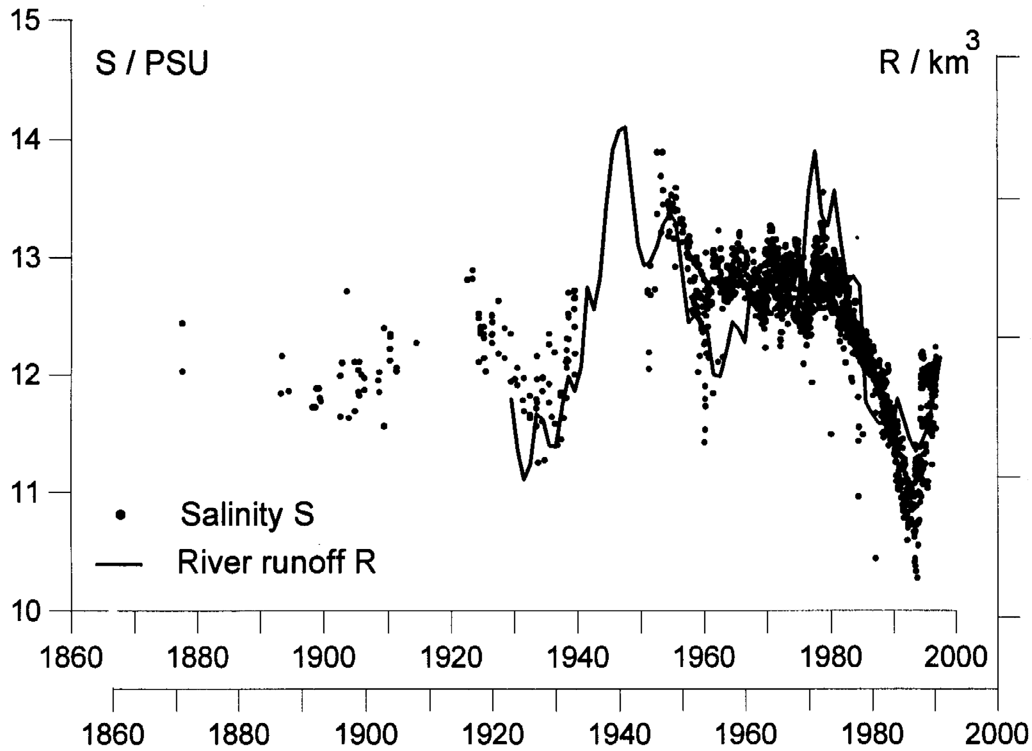

Figure 6. Long-term variations in river runoff to the Baltic Sea compared with the salinity in the central Baltic deep water (Gotland Deep: 200 m; Fårö Deep: 150 m; Landsort Deep: 400 m; Karlsö Deep: 100 m; location of stations in Figure 1). The salinity in the Gotland Deep shows real values. The values at the other stations are changed by +0.8 PSU (Fårö Deep), by +1.8 PSU (Landsort Deep) and by +2.6 PSU (Karlsö Deep). The time axis for runoff is shifted forward by 6 years.

role in the salt transport into semi-enclosed brackish sea areas like the Baltic Sea. That is true in particular for the occurrence and absence of major inflows of highly saline and oxygenated water which are the only mechanism by which living conditions are improved in the deep water below the permanent halocline.

Runoff variations affect the Baltic deep water by two mechanisms:

1. entrainment and mixing of low saline outflowing water in the surface layer into the higher saline water penetrating into the Baltic in the near-bottom layer of the sill areas. The increased water supply to the Baltic reduces the salinity of the outflowing downward mixed water and more strongly dilutes the inflowing higher saline water.
2. influence of runoff variations on the occurrence of major inflows. Reduced runoff favours inflow events. An increase in water supply to the Baltic Sea causes a greater outflow through the Danish Straits, reduces or impedes the inflow of saline water and gives rise to unfavourable conditions for MBI.

The runoff regime is the result of complex interactions. It is subject to precipitation, evaporation, changes in water storage, vegetation and land use in the drainage area and may be affected by human impacts, at least through changes in the annual runoff cycle due to river regulation.

Changes in the exchange process between North Sea and Baltic seem to be the main cause for the decrease in frequency and intensity of MBI since the mid-seventies and the complete absence of such events between February 1983 and January 1993. The decrease can be explained by increased atmospheric zonal circulation which transports wet air masses from the North Atlantic to Europe more frequently resulting in intensified precipitation in the Baltic region, lower evaporation and increased river runoff, thereby frequently causing above-normal Baltic sea levels for larger periods. During the past two decades, the anthropogenic impact on the freshwater cycle by redistribution of runoff due to river regulation is as high as never before and thereby gives rise to unfavourable conditions for inflows of saline water, and in particular for the occurrence of MBI, between November and April.

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References

Bergström, S. & B. Carlsson, 1994. River runoff to the Baltic Sea: 1950–1990. Ambio 23: 280–287.

Carlsson, B. & H. Sanner, 1994. Influence of river regulation on runoff to the Gulf of Bothnia. SMHI Reports Hydrology 9: 1–30.

Ehlin, U. & G. Zachrisson, 1974. Redistribution of runoff to the Baltic through river regulations in Sweden. Proc. 9th Conf. Baltic Oceanogr. Kiel: 265–274.

Ekman, M., 1996. Extreme annual means in the Baltic sea level during 200 years. Small Publ. in Histor. Geophys. 2: 1–15.

Fischer, H. & W. Matthäus, 1996. The importance of the Drogden Sill in the Sound for major Baltic inflows. J. Mar. Systems 9: 137–157.

Franck, H., W. Matthäus & R. Sammler, 1987. Major inflows of saline water into the Baltic Sea during the present century. Gerlands Beitr. Geophys. 96: 517–531.

Franck, H. & W. Matthäus, 1992. The absence of effective major inflows and the present changes in the hydrographic conditions of the central Baltic deep water. Proc. 12th Baltic Marine Biol. Symp., Helsingør 1991. In Intern. Symp. Series, Fredensborg: 53–60.

Gustafsson, B., 1998. Time-dependent modeling of the Baltic entrance area. Part 2: Water and salt exchange of the Baltic Sea Estuaries (in press).

Håkansson, B. G., B. Broman & H. Dahlin, 1993. The flow of water and salt in the Sound during the Baltic major inflow event in January 1993. ICES Statutory Meeting, Paper ICES 1993/C:57: 1–26.

Helcom, 1986. Water balance of the Baltic Sea. Baltic Sea Environm. Proc. 16: 1–174.

Helcom, 1996. Third periodic assessment of the state of the marine environment of the Baltic Sea, 1989–93; Background document. Baltic Sea Environm. Proc. 64B: 1–252.

Hupfer, P., Z. Mikulski & M. Börngen, 1983. Statistical analysis of river inflow to the Baltic Sea in the period 1921/70. Geod. Geophys. Veröff. R. IV, 38: 100–143.

Isemer, H.-J. & R. Lindau, 1998. Climatological estimates of precipitation and evaporation over the Baltic proper based on COADS. In: The Second Study Conf. on BALTEX. Int. BALTEX Secret., Publ. Ser. 11: 80–81.

Jacobsen, T. S., 1980. Sea water exchange of the Baltic – measurements and methods. The Belt Project, Natl. Agency Environm. Prot., Copenhagen: 1–106.

Jakobsen, F., 1995. The major inflow to the Baltic Sea during January 1993. J. Mar. Systems 6: 227–240.

Kõuts, T. & A. Omstedt, 1993. Deep water exchange in the Baltic proper. Tellus 45A: 311–324.

Kullenberg, G. E. B., 1977. Observations of the mixing in the Baltic thermo- and halocline layers. Tellus 29: 572–587.

Lass, H. U., R. Schwabe, W. Matthäus & E. Francke, 1987. On the dynamics of water exchange between Baltic and North Sea. Beitr. Meereskd. 56: 27–49.

Lass, H. U., 1988. A theoretical study of the barotropic water exchange between the North Sea and the Baltic and the sea level variations of the Baltic. Beitr. Meereskd. 58: 19–33.

Lass, H. U. & W. Matthäus, 1996. On temporal wind variations forcing salt water inflows into the Baltic Sea. Tellus 48A: 663–671.

Launiainen, J. & T. Vihma, 1990. Meteorological, ice and water exchange conditions. In Second periodic assessment of the State of the Marine Environment of the Baltic Sea, 1984–1988; Background document. Baltic Sea Environm. Proc. 35B: 22–33.

Lehmann, A., 1998. Modellierung der Wasser-, Salz- und Wärmebilanz der Ostsee. Final Rep., Institut für Meereskunde, Kiel: 1–22.

Matthäus, W., 1995. Natural variability and human impacts reflected in long-term changes in the Baltic deep water conditions – a brief review. Dt. Hydrogr. Z. 47: 47–65.

Matthäus, W. & H. Franck, 1992. Characteristics of major Baltic inflows – a statistical analysis. Cont. Shelf Res. 12: 1375–1400.

Matthäus, W. & H. Schinke, 1994. Mean atmospheric circulation patterns associated with major Baltic inflows. Dt. Hydrogr. Z. 46: 321–339.

Matthäus, W. & H. U. Lass, 1995. The recent salt inflow into the Baltic Sea. J. Phys. Oceanogr. 25: 280–286.

Mikulski, Z., 1982. River inflow to the Baltic Sea 1921–1975. Polish Acad. Sci./Polish National Committee IHP UNESCO, Warsaw.

Nehring, D. & W. Matthäus, 1991. Current trends in hydrographic and chemical parameters and eutrophication in the Baltic Sea. Int. Rev. ges. Hydrobiol. 76: 297–316.

Nehring, D., W. Matthäus, H.-U. Lass, G. Nausch & K. Nagel, 1995. The Baltic Sea in 1995 – beginning of a new stagnation period in its central deep waters and decreasing nutrient load in its surface layer. Dt. Hydrogr. Z. 47: 319–327.

Omstedt, A., L. Meuller & L. Nyberg, 1997. Interannual, seasonal and regional variations of precipitation and evaporation over the Baltic Sea. Ambio 26: 484–492.

Rydberg, L., 1987. Hydrography, oxygen and nutrient balance of the Kattegat and related phenomena. Thesis, Göteborg University, Dept. of Oceanography, 1–40.

Samuelsson, M., 1996. Interannual salinity variations in the Baltic Sea during the period 1954–1990. Cont. Shelf Res. 16: 1463–1477.

Sayin, E. & W. Krauss, 1996. A numerical study of the water exchange through the Danish Straits. Tellus 48A: 324–341.

Schinke, H., 1996. Zu den Ursachen von Salzwassereinbrüchen in die Ostsee. Meereswiss. Ber., Warnemünde 12: 1–137.

Schinke, H. & W. Matthäus, 1998. On the causes of major Baltic inflows – an analysis of long time series. Cont. Shelf Res. 18: 67–97.

Stigebrandt, A., 1983. A model for the exchange of water and salt between the Baltic and the Skagerrak. J. Phys. Oceanogr. 13: 411–427.

Stigebrandt, A., 1987. A model for the vertical circulation of the Baltic deep water. J. Phys. Oceanogr. 17: 1772–1785.

Wyrtki, K., 1953. Die Dynamik der Wasserbewegungen im Fehmarnbelt I. Kieler Meeresforsch. 9: 155–170.

Wyrtki, K., 1954.: Die Dynamik der Wasserbewegungen im Fehmarnbelt II. Kieler Meeresforsch. 10: 162–181.