BIOLOGICAL, PHYSICAL AND GEOCHEMICAL FEATURES OF ENCLOSED AND SEMI-ENCLOSED MARINE SYSTEMS

Edited by

E. M. Blomqvist

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Biological, Physical and Geochemical Features of Enclosed and Semi-enclosed Marine Systems

Proceedings of the Joint BMB 15 and ECSA 27 Symposium,
9–13 June 1997, Åland Islands, Finland

Edited by

E.M. Blomqvist, E. Bonsdorff and K. Essink

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Preface

This volume presents some of the results of the joint BMB 15 & ECSA 27 Symposium held in Mariehamn, Åland, Finland in June 1997. The aims of the symposium were to present and discuss contributions covering comparisons of biological, physical and (geo-)chemical features and processes of enclosed and semi-enclosed marine systems. Also included were responses to altered environmental conditions, and discussion of operational assessment and management related to these topics.

The symposium was a joint meeting organized by the Baltic Marine Biologists (BMB) and the Estuarine and Coastal Sciences Association (ECSA), gathering around 200 scientists from more than twenty nations. The meeting was hosted by the Husö Biological Station (Department of Biology, Åbo Akademi University). Co-organizers were the Åland University College, SW Finland Environment Centre and the Archipelago Research Institute (University of Turku). The organizing committee consisted of Ea Maria Blomqvist, Erik Bonsdorff, Erkki Leppäkoski, Pasi Laihonen, Ilppo Vuorinen and Bernt Ingmar Dybern (all for BMB), Victor N. de Jonge and Donald S. McLusky (for ECSA).

Financial support for this publication was received from the Maj & Tor Nessling Foundation, the Academy of Finland, the Research Institute of the Åbo Akademi University Foundation and Ålands Kulturdelegation.

The topics of the symposium were chosen partly with respect to the location of the symposium, the Åland Islands. This part of the Baltic Sea with over 6000 islands and skerries forms numerous steep environmental gradients. Secondly, many rapid and large scale changes that have been recorded in the Baltic and other marine ecosystems, particularly in the coastal waters, did merit proper scientific attention. The present issue (with in all 28 peer-refereed papers from the symposium) offers a broad view of these topics. The included contributions are not only from the Baltic Sea region, but also from other coastal and estuarine environments in Europe and elsewhere. It is our hope that this proceedings volume will serve as a good basis for reference within the given framework.

EA MARIA BLOMQVIST
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Guest Editors

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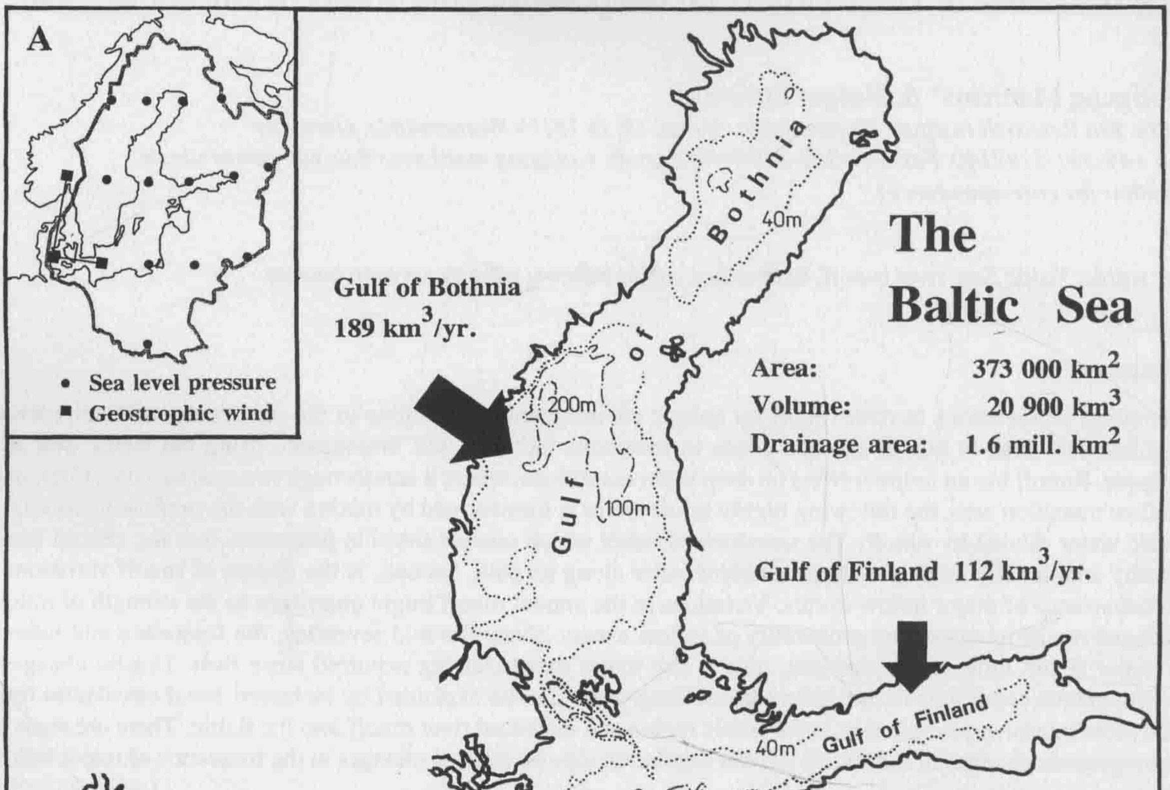

Figure 1. The Baltic Sea, its drainage area and the location of measurement stations. (Figures correspond to the Baltic Sea excluding Kattegat and Belt Sea). Arrows: mean annual contribution of river runoff to the Baltic Sea subbasins according to Bergström & Carlsson (1994).

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).

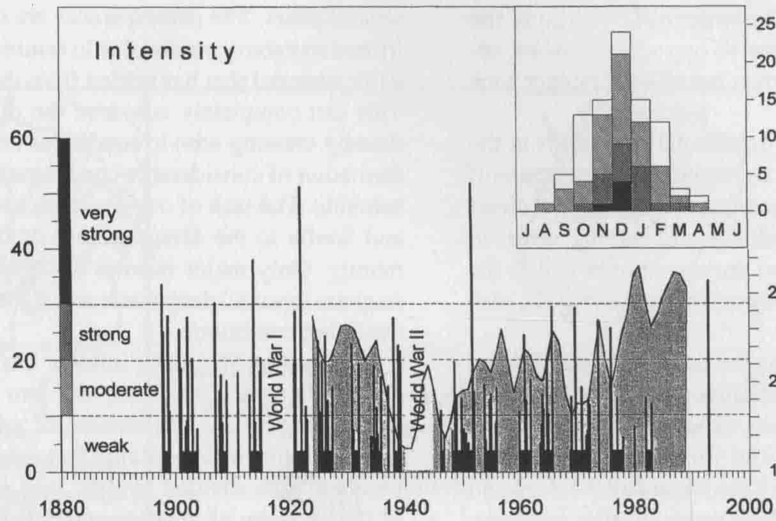

Figure 2. Major Baltic inflows (MBI) during the present century and their seasonal distribution (upper right) shown in terms of their strength (Matthäus & Franck, 1992; Fischer & Matthäus, 1996; updated) and low-pass filtered annual river runoff to the Baltic (inside the entrance sills) averaged from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

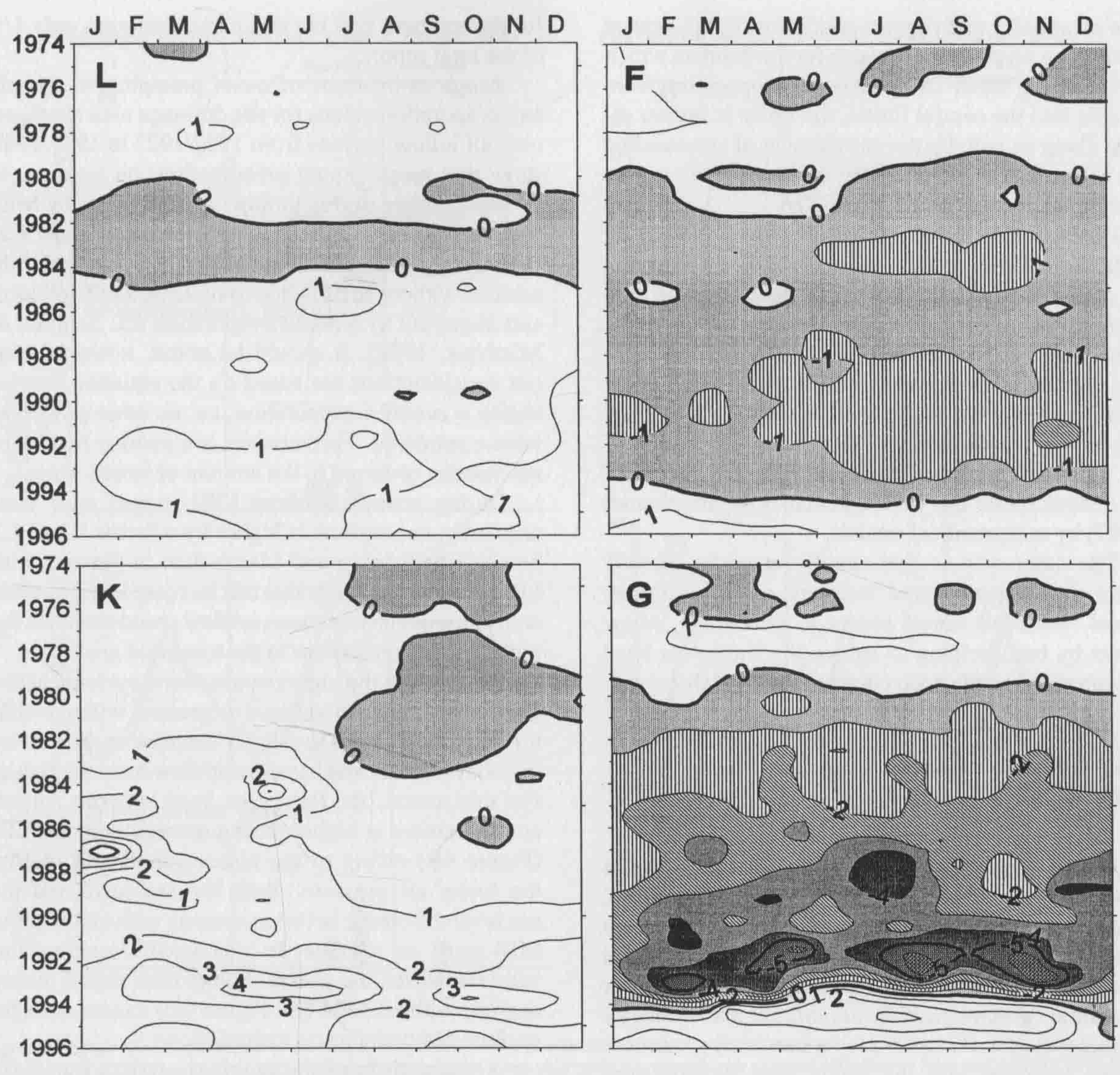

Figure 3. Variations in oxygen (>0) and hydrogen sulphide concentrations (<0, shaded) in the deep water of Landsort (L; 400 m depth), Karlsö (K; 100 m), Fårö (F; 150 m) and Gotland Deeps (G; 200 m) between 1974 and 1996 (for location of stations see Figure 1).

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).