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The history of investigation of salt water inflows into the Baltic Sea - from the early beginning to recent results

by

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STIG FONSELIUS on board of r/v "Argos" during his last visit of the central Baltic station "Gotland Deep" in January 1987 (Photo: J. Szaron).

This contribution is dedicated to my colleague and friend STIG H. FONSELIUS (1921 – 2003) who started systematic identification of major inflows of saline water into the Baltic Sea by means of variations in oceanographic parameters in the central Baltic deep water in the 1960s/1970s. His results were published in the three fundamental works on *"The hydrography of the Baltic deep basins"* I, II and III in 1962 – 1969. The basis of his investigations was the compilation of all observations available from the Baltic basins deep water. His investigation and chemical fieldwork was the continuation of the work which OTTO PETTERSSON started at the late 19th century with the first Baltic monitoring programme and KURT KALLE carried on in the field of marine chemistry in the 1930s.

Since the 1970s, I often met STIG FONSELIUS both during the field work in the Baltic Sea and during many meetings, conferences, workshops and symposia. He was an esteemed and appreciated colleague in the family of Baltic oceanographers because of his work on long-term environmental changes, his fundamental knowledge of the Baltic Sea problems but also for his bright and friendly humour.

Wolfgang Matthäus

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Abstract

This contribution represents a detailed description of the history of the investigation of major inflows of highly saline water into the Baltic Sea – termed major Baltic inflows (MBIs) - closely combined with the state-of-the-art MBI research. Starting with first information on the salinity conditions of the Baltic Sea, an overview of the various steps of investigating mechanism, causes and effects of MBIs is given. The period of observation of salt water inflows in the early 19^{th} century and the contribution of the great expeditions in the second half of the 19^{th} century to the investigation of MBIs are described. The importance of the international observation programmes for MBI research carried out during the early 20^{th} century is explained. Another topic is the analysis of selected events during the second half of the 20^{th} century. A chapter on the statistical analysis of the properties of MBIs summarized the methods for identifying MBIs, for estimation of their intensity and the volumes and properties of the inflowing water. The steps for investigation of the causes und preconditons for MBIs are explained. Moreover, the importance of barotropic and baroclinic warm water inflows into the Baltic Sea is described. Finally, the approaches for simulation of major events by numerical models are shortly compiled. A reference list of most of the publications on MBIs completes this contribution.

Kurzfassung

Dieser Beitrag gibt eine detaillierte Beschreibung der Geschichte über die Erforschung der großen Einströme salzreichen Wassers in die Ostsee – als Salzwassereinbrüche bezeichnet - eng verknüpft mit dem neuesten Stand ihrer Erforschung. Beginnend mit den ersten Informationen über die Salzgehaltsbedingungen in der Ostsee wird ein Überblick über die verschiedenen Schritte der Erforschung von Mechanismus, Ursachen und Auswirkungen von Salzwassereinbrüchen gegeben. Die Periode der Beobachtung von Salzwassereinbrüchen im frühen 19. Jahrhundert und der Beitrag der großen Expeditionen in der zweiten Hälfte des 19. Jahrhunderts zur Erforschung der Salzwassereinbrüche werden beschrieben. Auch die Bedeutung der internationalen Beobachtungsprogramme der ersten Hälfte des 20. Jahrhunderts für die Forschung über Salzwassereinbrüche wird erläutert. Ein weiterer Schwerpunkt stellt die Analyse ausgewählter Ereignisse in der 2. Hälfte des 20. Jahrhunderts dar. Ein Kapitel über die statistische Analyse der Eigenschaften von Salzwassereinbrüchen fasst die Methoden ihrer Identifizierung, zur Abschätzung ihrer Intensität und der Volumina und Eigenschaften des einströmenden Wassers zusammen. Die Schritte zur Erforschung der Ursachen und Vorbedingungen für Salzwassereinbrüche werden erläutert. Darüber hinaus wird die Bedeutung der barotropen und baroklinen Einströme warmen Wassers in die Ostsee beschrieben. Schließlich werden kurz Wege zur Simulation von Salzwassereinbrüchen mit Hilfe numerischer Modelle zusammengestellt. Eine Liste der Literaturangaben über die meisten Veröffentlichungen über Salzwassereinbrüche in die Ostsee rundet diesen Beitrag ab.

1. Introduction

The Baltic Sea (Fig. 1.1) is one of the largest brackish seas in the world. It is a landlocked intracontinental sea basin with a total area of 415,000 km^2 and a volume of 21,700 km^3 (including Kattegat). The environmental conditions of the Baltic are strongly dependent on the meteorological forcing over the sea, the hydrological processes in the catchment area and the oceanographic processes in the sea, as well as the interaction between them. These processes also influence the water exchange with the North Sea and between the sub-basins, as well as transport and mixing of water within the various sub-regions of the Baltic Sea.

Like other landlocked sea areas in humid regions at temperate latitudes, 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. Fig. 1.2 shows a schematic picture of the water balance of the Baltic Sea, the water exchange with the North Sea and the transformation of water masses in the Belt Sea.

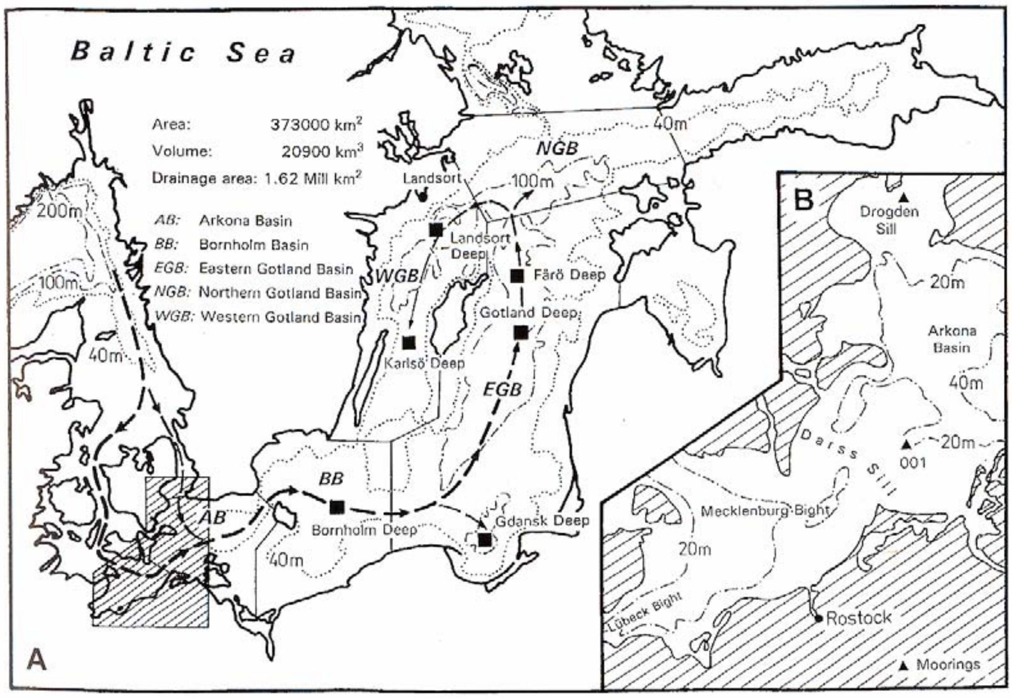

Fig. 1.1.
Sub-regions of the central Baltic Sea, their representative stations (squares), the main transport route of inflowing water during major Baltic inflows (arrows) (A) and the sill area (B). Figures correspond to the Baltic Sea inside the entrance sills.

Abb. 1.1.
Teilgebiete der zentralen Ostsee, ihre repräsentativen Stationen (Quadrate), der Haupttransportweg des bei Salzwassereinbrüchen in die Ostsee strömenden Wassers (Pfeile) (A) und der Bereich der Schwellen (B). Die Zahlenangaben beziehen sich auf die Ostsee ohne Kattegat und Beltsee.

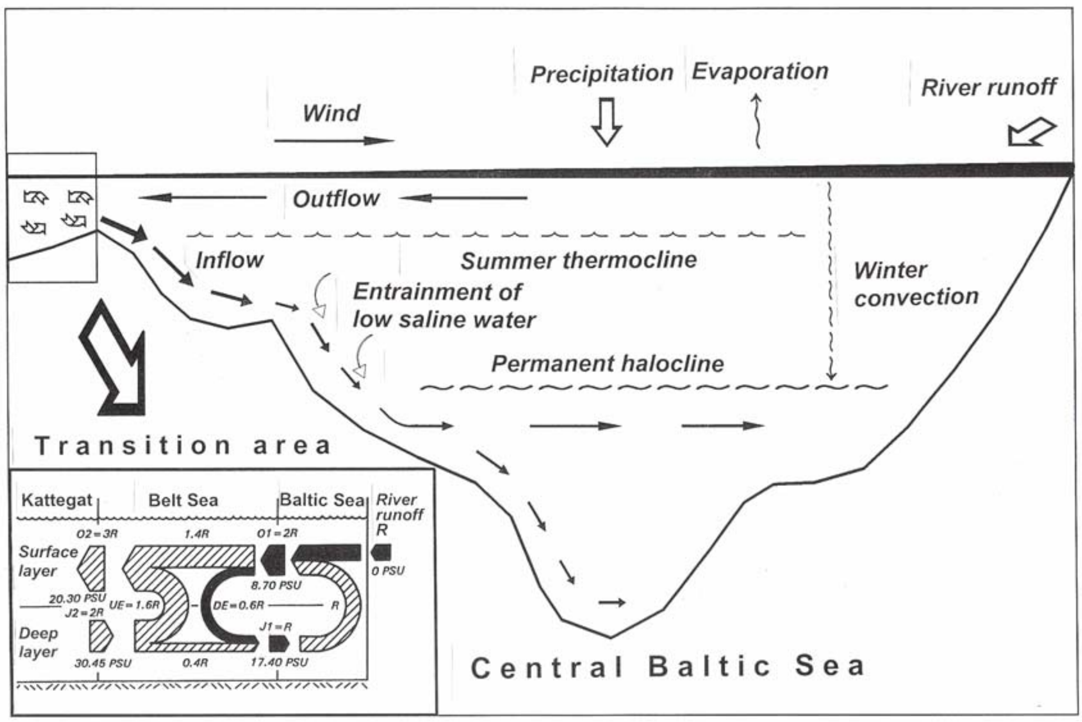

Fig. 1.2.
Schematic picture of the water balance of the Baltic Sea, the water exchange with the North Sea and the transformation of water masses in the Belt Sea (bottom left; in river runoff units).

Abb. 1.2.
Schematische Darstellung des Wasserhaushaltes der Ostsee, des Wasseraustausches mit der Nordsee und der Transformation der Wassermassen in der Beltsee (links unten; in Einheiten der Flusswasserzufuhr).

The salt balance of the Baltic is maintained by advection of salty North Sea water by both intermittent barotropic inflows and baroclinic inflows near the bottom. In general, there is an outflow of low saline water in the surface layer (O1, O2) and a compensation current transports higher saline water in the deep layer into the Baltic Sea (J1, J2; cf. Fig. 1.2). The mean annual fresh water surplus of the Baltic almost equals the volume of the annual inflow of saline water from the North Sea.

The water body of the central Baltic is permanently stratified, consisting of an upper layer of brackish water with salinities of about 6 - 8 PSU and a more saline deep water layer of about 10 – 14 PSU. A strong permanent halocline at depths between 60 and 80 m (cf. Fig. 1.2) prevents vertical circulation and, consequently, ventilation down to the bottom all the year round. During spring, a thermocline develops at 25 - 30 m depth and restricts additionally vertical exchange within the upper layer until late autumn. The horizontal deep water circulation is restricted by a series of sub-basins separated by submarine sills.

Oceanographic conditions in the deep water of the Baltic Sea are strongly influenced by inflows of saline and oxygenated water from the North Sea. Such inflows are, however, restricted by narrow channels (Little Belt, Great Belt, Sound) 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; location cf. Fig. 1.1B) in the transition area between the two seas, and the deep water in the central basins tends to stagnate for periods of several years. The consequences are depletion of nitrate, increasing phosphate and ammonium concentrations, decreasing salinity, oxygen depletion and, sometimes, ultimately the formation of hydrogen sulphide in the deep basins.

The transformation of water masses occurs mainly in the Belt Sea (Fig. 1.2, bottom left). There is an entrainment of water from the deep layer into the surface layer (UE) and vice versa (DE). During strong inflows, a complete mixing of the whole water body in the Belt Sea occurs. Additional transformation areas for the highly saline water penetrated during inflow events are the Arkona Basin (LASS and MOHRHOLZ 2003, MOHRHOLZ et al. 2006) and the Stolpe Channel (PIECHURA and BESZCZYŃSKA-MÖLLER 2004).

Strong inflow activities in early autumn transports warmer, inflows in winter and spring cold water into the central Baltic deep basins. The main transport route of inflowing water from the sills into the central basins is given in Fig. 1.1A. New observation techniques available during the recent decade have shown that the inflow process from the sills into the Bornholm Basin, through the Stolpe Channel and into the Gotland Basin has a complex dynamics. The pathways of the inflowing water propagating from the Darss and Drogden Sills through the Arkona Basin into the Bornholm Basin have been recently studied in detail (LASS et al. 2005). PAKA (1996) and ZHURBAS and PAKA (1997) studied the pathways of saline water from the Stolpe Channel into the eastern Gotland Basin. The inflowing water has internal fronts with fine-scale intrusions, surface and subsurface eddies and partly distinct higher current speeds as suggested (HAGEN and FEISTEL 2001). The flow of higher saline water over the Stolpe Sill has frequently a splash-like nature (PIECHURA et al. 1997).

The propagation of the inflowing water is additionally restricted by the bottom topography, and the effects of inflows are always reduced by the mixing of the penetrated water body with the ambient water along its path into the central Baltic (KÕUTS and OMSTEDT 1993; cf. also Fig. 1.2).

The volume of water with a higher salinity crossing the sills during the very frequent but weak inflows (10 - 20 km^3) have little impact on the deep and bottom waters. Such inflows are generally insufficient to displace the bottom water or significantly change oceanographic conditions in the Baltic deep basins because their water will be interleaved in or flow just beneath the permanent halocline (cf. Fig. 1.2). Episodic inflows of larger volumes (100 - 250 km^3) of highly saline (17 – 25 PSU) and oxygen-rich water which penetrates deeply into the Baltic, filling each of the chain of deep basins along the Baltic floor, represent the most important mechanism by which the Baltic deep water is displaced and renewed to a significant degree. Such inflows are a basic oceanographic phenomenon of the Baltic Sea.

For this process, WYRTKI (1953, 1954b) introduced the German term “Salzeinbruch” which was later changed into “Salzwassereinbruch” (FRANCKE and NEHRING 1971). In English written papers, the terms “salt water inflow” or “salt inflow” are used. The most frequently used term “major Baltic inflow (MBI)” was coined by DICKSON (1971, 1973).

The volume of highly saline water passing into the Baltic across the Drogden Sill (cf. Fig. 1.1B) is generally thought to be insufficient to renew the central Baltic deep water significantly. In the majority of events investigated, far more salt enters the Baltic across the Darss Sill. Therefore, only the transport of larger volumes across the Darss Sill supported by the inflow across the Drogden Sill constitutes a major inflow.

A total of 113 major inflows has been identified since 1880 excluding the two world wars (cf. Fig. 6.2). All MBIs have occurred between the end of August and the end of April. The seasonal frequency distribution of MBIs (Fig. 6.2, top right corner) shows that such events are most frequent between October and February and less common in August/September and in March/April. Major events have never been recorded between May and mid-August. MBIs usually occur in clusters, but some have been isolated events. Most clusters had a duration of several years, the longest being recorded from 1948 to 1952. The longest periods without an inflow event before the late 1970s lasted for three years (1927/1930, 1956/1959), but ten years passed without a major event between February 1983 and January 1993 (cf. Fig. 6.2).

The variability in atmospheric circulation governs the water exchange of the Baltic with the ocean, especially the occurrence or absence of major inflows (MATTHÄUS and SCHINKE 1994; GUSTAFSSON 2000). MBIs have an essential impact on the oceanographic conditions in the deep water (temperature, salinity, oxygen, inorganic nutrients). There are indications that MBIs may also affect the transformation of contaminants (PAHs) and the modification of their distribution in the deep water (cf. WITT and MATTHÄUS 2001). There seems to be an impact of runoff variation on the occurrence of MBIs. Drastic changes in environmental conditions in the 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 (MATTHÄUS and SCHINKE 1999; HÄNNINEN et al., 2000; ZORITA and LAINE 2000). LAUNIAINEN and VIHMA (1990) demonstrated a correlation between river runoff and Baltic deep water salinity (cf. also SAMUELSSON 1996). There is also a connection between oxic/anoxic conditions and the concentration of inorganic nutrients (FONSELIUS 1962, 1967; NEHRING 1987, 1989).

Since the 1960s, the Institute of Marine Research (Institut für Meereskunde Warnemünde) and later the Baltic Sea Research Institute in Warnemünde (Leibniz-Institut für Ostseeforschung Warnemünde, IOW) were largely involved in the investigation of major Baltic inflows by numerous basic investigations und analyses. Both MATTHÄUS and FRANCK (1992) and SCHINKE and MATTHÄUS (1998) summarized the current knowledge on the characteristics and causes of MBIs. In 2003, NEHRING appreciated the contributions of the research institutes in Warnemünde to the investigation of MBIs in a short retrospective view (NEHRING 2003).

However, a detailed representation on the history of the investigation of major Baltic inflows is missing so far. This contribution shall fill the gap in history in combination with the state-of-the-art in investigation of major inflows of saline water into the Baltic Sea.

2. The early period of observations

Basis for the investigation of the mechanism, the causes and effects of inflows of salt water into the Baltic Sea was both the development of methods for determination of salinity and the investigation of the salinity in the Baltic Sea itself. However, before methods for salinity measurements were developed it could be provided evidence of major inflows of salty water by means of the occurrence of larvae and other organisms regularly native to the Kattegat and the North Sea.

2.1 From the early beginnig to the first national observation programmes

The oldest information on properties of the Baltic Sea water are from Swedish observations (cf. FONSELIUS 2001, 2002). At the late 18th century, the physicist JOHAN CARL WILCKE (1731 – 1796) analyzed the properties of sea water of the Baltic (WILCKE 1771). PETER JOHAN BLADH (1776) measured temperature and density in the Sound, along the Swedish Baltic coast, in the Åland Sea and the Gulf of Bothnia.

Information on salinity and the causes for the salt in the Baltic Sea go back to the beginning of the 19th century. It was found out that the salinity in the Baltic Sea was lower than in the ocean. In 1815, JEAN PIERRE GUILLAUME CATTEAU-CALLEVILLE reported among other things on salinity, density and temperature of the Baltic Sea. He stated that the Baltic has still a smaller salinity as the other nordic seas

> "…wegen ihrer abgesonderten Lage und der großen Menge von Flußwasser, das sich unaufhörlich in dieselbe ergießt." (CATTEAU-CALLEVILLE 1815, p. 127).

On 20 May 1819, ALEXANDER J. G. MARCET reported to the Royal Society of London on aerometric and chemical analyses of sea water samples from different parts of the ocean (MARCET 1819, cf. also GILBERT 1819). He also analyzed three samples from the Baltic Sea, the Sound and the Kattegat and stated:

> "It may be stated generally, that small inland seas, though communicating with the ocean, are much less salt than the open ocean. This is particularly striking in the case of the Baltic;…" (MARCET 1819, p. 174).

In 1820, the editor of the *Annalen der Physik* LUDWIG WILHELM GILBERT (1769 – 1824) informed on the following sentence, written in a letter of lieutenant DE FRÉMINVILLE to Mr. BRONGUIART:

> "In dem Liefländischen Meerbusen ist das Wasser der Ostsee noch minder salzig als irgendwo anders;…" (GILBERT 1820, p. 163).

At another place, GILBERT reported on observations of Mr. von SIVERS on the saltiness of the water in the Baltic Sea and in the Sound. During a voyage from Riga to Copenhagen and Helsingør in 1819, he observed salinities between 7 PSU in the Gulf of Riga, by 8 PSU near Gotland and about 15 PSU in the northern part of the Sound (von SIVERS, 1820).

The effect of winds on the inflow of salt water was detected relatively early. CATTEAU-CALLEVILLE explained as cause for the transport of salt into the Baltic:

> "Die Sued- und Suedwest-Winde…vermehren den Salzgehalt im ganzen Meere, weil sie Wasser aus dem Ocean hineinbringen" (CATTEAU-CALLEVILLE 1815, p. 128).

First evidence of the transport of deep water in direction to the Baltic Sea refer to the existence of undercurrents in the depth of the Belts and the Sound. In 1821, Captain (later Admiral) PHILIP PATTON found an undercurrent in the Sound near Helsingør. DAVID BREWSTER (1821) informed over that in the *Edinburgh Philosophical Journal*, p. 245:

> "A submarine current…has been observed by the…Captain Patton, R. N. The ship…having had occasion to anchor some miles from Elsinore, he found a current running from the Baltic, at a rate of *four* miles an hour by the log. Upon dropping the lead,…he found the line continue perpendicular from his hand, when the lead itself was raised a little from the ground. Hence he concluded, that an under-current, equally rapid with that on the surface, had prevented the lead and line from yielding to the opposite motion of the fluid, as it would have done had the ship been sailing at that rate through the water."

In 1858, the Danish chemist JOHAN GEORG FORCHHAMMER (1794 – 1865) reported on undercurrents near Helsingør which transported water with higher salinity into direction to the Baltic:

> "…altid gaaer en Understrøm ind i Østersøen, der har mere saltholdigt Vand,…" (FORCHHAMMER 1858, p. 62).

In 1859, ANTON von ETZEL compiled the knowledge of his time on geography, natural science and history of the Baltic Sea in the book *"Die Ostsee und ihre Küstenländer"* (ETZEL, 1859).

> "Das baltische Meer ist…in Folge zahlreicher Regen, des geschmolzenen Schnees, und der großen Menge Flußwassers, das ihm unaufhörlich zugeht, viel weniger reich an Salzgehalt als die anderen Meere." (ETZEL 1859, p. 214).

Moreover, the salinity varies regionally:

> "In der Ostsee..." there are "…große Verschiedenheiten in verschiedenen, sich naheliegenden Gegenden und Tiefen, die abhängig von den Jahreszeiten und Winden sind. Im Süden ward der Salzgehalt stärker gefunden als im Norden, im hohen Meer bedeutender als in den Buchten und Meerengen,..." (ETZEL 1859, p. 214/215).

ETZEL coined the term „Einbrüche des Oceans" in connection with the inflow of water into the Baltic Sea. He wrote on this phenomenon:

> "Wenn die Nordsee z.B. durch Südsüdwest-Winde bewegt ist, wälzen sich ihre Wogen nach Ost und treten in das Kattegat hinein, dessen ihr entgegenkommende Ausströmungen zurückgestoßen werden, und ihrerseits wieder die des baltischen Meeres zurückstoßen. Dieses Phänomen wird noch auffallender, wenn der Wind aus Nordwesten längere Zeit hindurch im Oceane herrscht; dann werden die Gewässer...längs der Küsten Jütlands und des westlichen Schwedens gehen. Diese rückgängige Bewegung macht sich sogar mitunter bis in die Buchten von Bothnien und Finnland bemerkbar,..." (ETZEL 1859, p. 201).

In 1864, HEINRICH STRUVE investigated the surface salinity in the Baltic Sea. He assumed that a „two-fold" current exists in the Baltic. His assumption based upon

> "…dass im Becken der Ostsee sich zwei Wasser vermischen, nämlich die Süsswasser aus den mächtigen Zuflüssen...mit dem Meerwasser aus dem grossen Ocean, das durch den Sund und die beiden Belte hineinströmt..." (STRUVE 1864, p. 9).

In another place, he stated that

> „…Strömungen in der Ostsee und zwar in dem eigentlichen grossen Becken derselben...durch den verschiedenen Salzgehalt im Wasser hervorgerufen werden..." (STRUVE 1864, p. 11).

STRUVE is of the opinion that the existence of such currents can be verified only

„…durch…Untersuchungen des Seewassers aus verschiedenen Tiefen“ (STRUVE 1864, p. 9).

In 1867, ARTHUR FERDINAND BARON SASS reported on variations of salinity in the Baltic Sea (SASS 1867). He studied relations between salinity and wind direction and force, season and precipitation.

The merchant and factory owner HEINRICH ADOLPH MEYER (1822 - 1889) was one of the first who investigated the physical conditions in the western Baltic Sea. Between 1868 and 1870, he carried out regular measurements at fixed stations and during two cruises in the Little Belt, the Great Belt, the Sound and the Kiel Bight (MEYER 1871). He studied the interaction of salinity and wind, sea level and currents in the transition area between the North Sea and the Baltic.

MEYER carried out monthly observations of the currents in the Great Belt between Korsör and Sprogö Island. However, he complained that

> “...ein gleichmässiges Strommaass und die Erfindung eines für obere und untere Strömungen brauchbaren Geschwindigkeitsmessers...“

are still missing and he recommended that

> „...bei einigen meteorologischen Stationen schon eingeführte Instrumente zur Messung der Windstärke...“

should be generally used (MEYER 1871, p. 33).

Already 1868 he identified two-layer currents (he called it “Doppelströmungen”): out-going currents at the surface (Oberstrom = upper current) and in-going currents in the deeper water layers (Unterstrom = under current). MEYER concluded:

> “Der ungleiche Salzgehalt der Nordsee und Ostsee...ist die Ursache von Doppelströmungen in den, beide Meere verbindenden Wasserstrassen...“ „Das salzreiche, specifisch schwerere Wasser der Nordsee dringt als Unterstrom in die Ostsee ein, das salzärmere, specifisch leichtere Wasser der Ostsee fliesst als Oberstrom in das Kattegat und die Nordsee“ (MEYER 1871, p. 46).

As far as the salinity of the Baltic Sea is concerned MEYER generally stated:

> “Das Oberflächenwasser ist im Allgemeinen immer salzärmer als das Tiefenwasser…” (MEYER 1871, p. 20).

He concluded

> “…dass es hauptsächlich der viel salzreichere, überwiegend eingehende Unterstrom ist, welchem die Ostsee die stete Erneuerung des Salzgehaltes verdankt...“ (MEYER 1871, p. 46).

Increasing wind between WNW and NW causes a strengthening of the undercurrent.

As early as in 1871, the undercurrent of salt water into the Baltic Sea through the Sound was also mentioned in the scientific journal *Nature* (ANONYMOUS 1871). In the

“…Baltic Sound…, as was long ago experimentally shown (with a result that has recently been confirmed by Dr. Forchhammer), a deep current of salt water flows inwards from the North Sea, whilst a strong current of brackish water sets outwards from the Baltic…” (ANONYMOUS 1871, p. 98).

MEYER (1871) reported that the transport of salt into the Baltic Sea, caused by the wind, is influenced by three factors:

> "…a) durch die Wellenbildung, b) durch den Einfluss auf die Höhe des Wasserstandes in der Ostsee, c) durch den Einfluss auf die Geschwindigkeit der Strömungen." (MEYER 1871, p. 46).

He described the interaction between wind and salt transport:

> „...Winde können...bald verstärkend bald schwächend für den Eintritt des salzreicheren Wassers wirken..." (MEYER 1871, p 24).

MEYER already distinguished between different intensities of the inflow caused by the wind conditions:

> „...die Wirkung kann dem allgemeinen Oberstrom entgegen sein, ihn verlangsam, hemmen, umkehren und den eingehenden Unterstrom beschleunigen, (intensive und andauernde westliche Windrichtung)" (MEYER 1871, p. 47).

Furthermore he concluded:

> „...unter welchen günstigen Verhältnissen das salzreiche Wasser...weit in die Ostsee einzudringen und ihre Tiefen zu erfüllen vermag,...ist...der wechselnde Erfolg mannigfacher Einflüsse..." (MEYER 1871, p. 25).

During the last decades of the 19th century, national observation programmes started in the countries around the Baltic Sea (cf. SMED 1990, PETTERSSON 1896). All these programmes also supported ultimately the investigation of inflows into the Baltic. From 1891, regular seasonal cruises were carried out in the transition area by Danish ships (RØRDAM 1896, WANDEL 1896). Two profiles of special importance were selected: the profile across the northern entrance to the Kattegat and the profile Gedser Rev – Darss, where the deep water inflow into the Baltic takes place. RØRDAM (1896) worked up and published the observations made 1891 – 1893 and KNUDSEN (1899) worked up thoroughly the observations carried out between 1894 and 1898. On the basis of the relatively few observations KNUDSEN raised more principal questions among them the water exchange between the North Sea and the Baltic.

The experience of the member countries from national observation programmes in the late 19th century formed the basis that – in 1902 – a detailed programme for hydrographic investigations could be implemented without delay by the International Council for the Exploration of the Sea (ICES).

2.2 The contributions of OTTO KRÜMMEL and MARTIN KNUDSEN

KRÜMMEL (1894, 1895) and KNUDSEN (1899, 1900a, b) were investigating the problem of renewal of the Baltic deep water as early as the end of the 19th century.

The pioneer of the progressive oceanography in Germany, OTTO KRÜMMEL (1854 – 1912) summarized the knowledge of that time on the physics of the Baltic Sea. In 1894, he analysed the data available up to 1894 which based on the observations on board of the German paddle-wheel steamer "Pommerania" in 1871 and measurements carried out by the Swedish physicist FREDERIK L. EKMAN in 1877 (published by OTTO PETTERSSON 1893), by the Russian Admiral STEPAN O. MAKAROFF in 1886 and 1889 (MAKAROFF 1894) (cf. also chapter 3) and his own measurements (KRÜMMEL 1894). He was still of the opinion that

"…durch den…nur 7 m tiefen Sund sogut wie niemals schwereres Wasser aus dem Kattegat in die Ostsee vordringt,...Dagegen ist es hauptsächlich der tiefe Große Belt,....durch deren Tiefen das schwere Wasser gewöhnlich seinen Einzug hält" (KRÜMMEL 1894, p. 138).

Although the number of open sea measurements was small it was observed that

„...sich in den isolirten trogartigen Mulden der Ostsee Wasser von auffallend viel größerer Salinität findet..."

That can be explained

„...durch die Wirkung der Winde...Westwinde drücken das Ostseewasser von Rügen hinweg nach der...Finnischen Küste zu, und gewähren dann dem salzhaltigeren Wasser des Kattegats, besonders in der Tiefe, Zutritt und können es so bis in die Hauptmulde bei Gotland gelangen lassen" (KRÜMMEL 1894, p. 138).

In particular, he analyzed the inflow situation of the Bornholm Basin at the end of the 19th century:

"Zwischen 1871 and 1877 hat vielleicht eine Zufuhr neuen Wassers aus der Beltsee stattgefunden…Dagegen hat von 1877 bis 1893 eine deutlich erkennbare Aussüßung...stattgefunden, während bis Juli 1894...wieder eine Zufuhr neuen Wassers über die Darßer Schwelle erfolgt ist..." (KRÜMMEL 1985, p. 86).

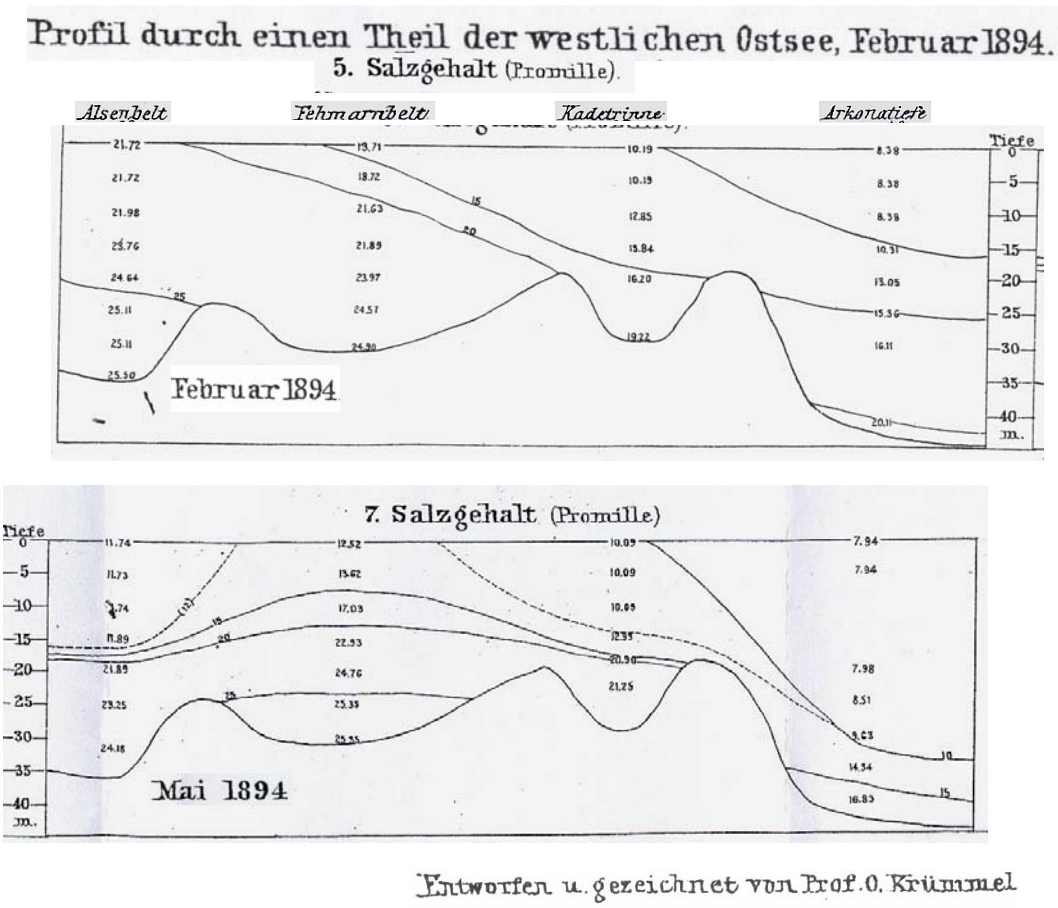

Fig. 2.1.
Longitudinal transects of salinity across the Darss Sill in February and May 1894 (drawing by O. KRÜMMEL 1895, Table 5).

Abb. 2.1.
Längsschnitte des Salzgehalts über die Darßer Schwelle im Februar und Mai 1894 (gezeichnet von O. KRÜMMEL 1895, Tabelle 5).

He stated that the salt water in the central Baltic deep basins

> "…notwendig über die Darßer Schwelle…eingetreten sein muß,…Das Vordringen dieses Tiefenwassers ins Innere der Ostsee wird…wesentlich reguliert durch die Schwellen- oder Zugangstiefen, welche die einzelnen Trogmulden voneinander trennen" (KRÜMMEL 1895, p.85/86).

KRÜMMEL (1895) identified the weak MBI in February 1894, observed the salinity distribution in the western Baltic in February and May 1894 (cf. Fig. 2.1 and 6.2) and its effect in the Bornholm Basin. He assumed that salt water

> "…nur in Perioden von langer Dauer Zutritt findet…wie wir das Wasser in der Tiefe östlich von Bornholm…sich haben erneuern sehen in der Zeit von November 1893 bis Juli 1894" (KRÜMMEL 1895, p. 117).

His measurements showed an increase in near-bottom salinity between November 1893 and July 1894 (KRÜMMEL 1895, p. 86).

As early as 1899 the Danish physicist and oceanographer MARTIN KNUDSEN (1871 – 1949) published investigations on the water exchange across the Drodgen and Darss Sills (KNUDSEN 1899, 1900a, b). His paper on the *„Erneuerung der unteren Wasserschichte in der Ostsee"* (KNUDSEN 1900a) represents a fundamental work on the renewal of the central Baltic deep water.

He stated that considerable amounts of water flow across the Danish Straits into the Baltic Sea. He calculated that the inflow of salty water into the Baltic is about half the amount of the outflow with the Baltic current in a certain period:

> „Es strömt ... doppelt so viel Wasser durch die Ablaufsöffnungen der Ostsee aus, als einströmt,..." (KNUDSEN 1900b, p. 318).

Moreover, he stated that

> "…diese Zufuhr nicht zu jeder Zeit stattfindet, sondern intermittirend ist." (KNUDSEN 1900a, p. 586).

The deep water of the Baltic is renewed by the

> „...stoßweise Zuströmung von der Kadetrinne..." (KNUDSEN 1900a, p. 587).

KNUDSEN wrote at another place on the salinity of the inflowing water necessary for the renewal of the upper part of the deep water

> "Wie salzig das durch die Kadetrinne einströmende Wasser sein muß, um den oberen Theil der Unterschichte erneuern zu können...wird von der Dauer und der Menge der Einströmung abhängen" (KNUDSEN 1900a, p. 586)

and that a salinity of 17 PSU in the Kadet Channel is not sufficient,

> „...um eine Erneuerung des unteren Theiles der Unterschichte (des Bodenwassers) östlich von Bornholm bewirken zu können" (KNUDSEN 1900a, p. 586).

He identified four inflow periods in 1897 by means of the salinity observations at the Danish light vessels among them the very strong inflow between the 20 November and 4 December 1897 (cf. Fig. 6.2 and No. 6 in Table 6.2). He stated that the salinity of the water passing the Sound into the Baltic is higher than the salinity of the water volume crossing the section Gedser – Darsser Ort.

On the other hand, he was of the opinion:

> "Selbst wenn…bedeutende Mengen salzigen Wassers durch den Sund einströmen können, wird die größte Menge salzigen Wassers der Ostsee doch durch den Schnitt Gjedser – Darsser Ort zugeführt werden. Hier wird der Salzgehalt nie so hoch, als er bei Drogden werden kann, aber wenn er höher als der Salzgehalt der Ostsee wird, so kann er sich viel länger hoch halten, als es bei Drogden der Fall ist" (KNUDSEN 1900a, p. 589).

KRÜMMEL described the basic inflow mechanism and the renewal of the central Baltic deep water in his lecture *"Die Deutschen Meere im Rahmen der internationalen Meeresforschung"*, presented in the Institut für Meereskunde in Berlin in 1903 (KRÜMMEL 1904). However, there is no direct reference to MBIs but he described that inflows of saline water into the Baltic

> "…nicht kontinuierlich, sondern unregelmäßig, stoßweise erfolgen und das zugeführte Quantum in jedem Fall verschieden groß ausfallen" (KRÜMMEL 1904, p. 27).

He reported on the propagation of the water penetrated during the strong MBI in December 1902 (Q_{96} = 20.3; cf. No. 26 in Table 6.2) and on the renewal process in the Baltic Sea. He demonstrated the renewal process by the increase in oxygen in the Gdańsk Deep:

> "Daß es sich…um eine Erneuerung des Wassers gehandelt hat, wird…erwiesen durch den Sauerstoffgehalt…; er betrug im November 1902 nur 6 Prozent, dagegen im Mai 1903...25 Prozent…und maß im Februar 1904 nur 9 Prozent" (KRÜMMEL 1904, p. 31).

Despite the small number of observations the basic principle of the water renewal of the central Baltic deep water was revealed and already included in oceanographic manuals of that time. KRÜMMEL, e. g., summarized the knowledge on the renewal process in his famous *„Handbuch der Ozeanographie"* by the following sentences:

> „Die Mulden der Ostsee erneuern ihr Tiefenwasser unregelmäßig und schubweise; die Rügensche und Bornholmer Mulde alljährlich, meist einmal, seltener zweimal, die Danziger Mulde fast alljährlich, die Gotland- und die bottnischen Tiefen oft erst nach vielen Jahren, alle erhalten das neue Tiefenwasser aus der Beltsee oder seltener auch aus dem Öresund." (KRÜMMEL 1907, p. 301).

He remarked on the indicators for a renewal of the deep water:

> "…der Salzgehalt gewährt dafür…nur *ein* Merkmal, ein empfindlicheres…die Temperatur, am deutlichsten sprechen aber die gelösten Gase " (KRÜMMEL 1907, p. 352).

On the causes of the decreasing oxygen in the deep water, he commented:

> "Während der Stagnierperioden wird der Sauerstoff teils von den Tieren zur Atmung verbraucht, teils tritt eine Reaktion zwischen ihm und der im Wasser gelösten organischen Substanz ein, die sowohl durch Diffusion aus dem Bodenschlamm, wie durch abgestorbenes Plankton zugeführt wird." (KRÜMMEL 1907, p. 301).

3. The great Baltic Sea expeditions during the 19th century

In the late 19th century, several important expeditions were carried out in order to investigate the physical, chemical and biological conditions of the Baltic Sea. These expeditions yielded among others essential knowledge on the mechanism of water exchange across the Belts and the Sound and the propagation of salt water within the Baltic Sea. The observations have been evaluated in detail by KRÜMMEL (1894, 1895) and KNUDSEN (1899, 1900a, b) (cf. chapter 2.2).

In the summer of 1871, the German „Commission zur wissenschaftlichen Untersuchung der deutschen Meere in Kiel" organized the first important expedition for investigation of the oceanographic conditions of the Baltic Sea (MEYER et al., 1873). Basic objective of the expedition carried out on board of the paddle wheel steamer "Pommerania" was, among others,

> "…welches Wasser…durch Sund und Belte in die Ostsee…eintreten kann…und…der Verlauf der Verdünnung bis in das…östliche Gotlandbecken…" (JACOBSEN, 1873, p. 39).

O. JACOBSEN wrote on the pathway of the salty water into the Baltic

> "…dass für das Eintreten des Wassers aus dem Kattegat, nicht der Sund, sondern der grosse Belt die weitaus grössere Bedeutung habe" (JACOBSEN, 1873, p. 39).

He stated on the further penetration of the saltwater:

> „…tiefere Schichten salzreichen Wassers…erstrecken sich bis weit in die Ostsee hinein, - nur langsam durch allmälige Mischung mit schwächerem Oberflächenwasser an Salzgehalt verlierend und im Allgemeinen den Rinnen der grössten Tiefen als vorgeschriebenen Strombetten folgend" (JACOBSEN, 1873, p. 40).

As far as salinity is concerned results showed:

> "…in der Ostsee…lässt sich…eine Zunahme des specifischen Gewichtes von Oben nach Unten nachweisen. Da ein Abnehmen des Salzgehaltes vom atlantischen Ocean...zur Ostsee...von Westen nach Osten vorhanden ist,...findet...eine Bewegung des Wassers...der Art statt, dass sich das schwerere Wasser unten...von West nach Ost, das leichtere oben...von Ost nach West bewegt" (KARSTEN 1874, p. 513).

The physicist and mineralogist GUSTAV KARSTEN (1820 – 1900) stated on the causes of inflows of saline water into the Baltic Sea:

> "Vorherrschend westliche und südwestliche Winde führen…der Ostsee von der Nordsee mächtigere Unterströmungen schwereren Wassers zu....Mit den klimatischen Verhältnissen in Uebereinstimmung stehend..." penetrates „...daher durchschnittlich im Herbst und Winter salzigeres Wasser bis in die Ostsee..." (KARSTEN 1874, p. 514); „...wenn die westliche Windrichtung längere Zeit andauert, wird...allmälig, wie ...vor der Novembersturmfluth des Jahres 1872,...das ganze westliche Becken der Ostsee mit salzreichem Wasser erfüllt werden..." (KARSTEN 1874, p. 516).

Fig. 3.1 shows the salinity distribution between Fehmarn Belt and the Arkona Basin in August 1871 measured by the "Pommerania". The Belt Sea boundary hits the western slope of the Darss Sill and saline water >13 PSU penetrates into the Arkona Basin.

The results of the "Pommerania"-expedition in 1871 were included in the first oceanographic manual published by GEORG von BOGUSLAWSKY (1827 - 1884), who made the earliest efforts to condense the knowledge in oceanography in a manual. There is written on the saline deep current into the Baltic Sea:

> "…dass…die jeweilig längere Zeit herrschenden Winde und andererseits ungewöhnlich hohe Niederschläge einen wesentlichen Einfluss auf die Intensität und Verbreitung des salzreicheren Tiefenstromes ausüben und ein Vordringen desselben in der Tiefe weiter nach Osten...veranlassen können" (BOGUSLAWSKY 1884, p. 168).

The Swedish expeditions on board of the gunboat "Alfhild" and the survey ship "G. af Klint" in the summer of 1877 under chief scientist FREDERIK L. EKMAN were the most important and detailed investigations in the whole Baltic Sea during the 19th century (EKMAN and PETTERSSON 1893). More than 200 stations covering the entire Baltic Sea were investigated and temperature and salinity were measured. The oceanographer OTTO PETTERSSON (1848 – 1941) – he is considered to be the father of the oceanography in Sweden - worked out and published the results after the death of EKMAN in 1890 and compared them with the results from the "Pommerania" (PETTERSSON 1893). He concluded that deep stretching changes in the deep water had occurred between 1871 and 1877.

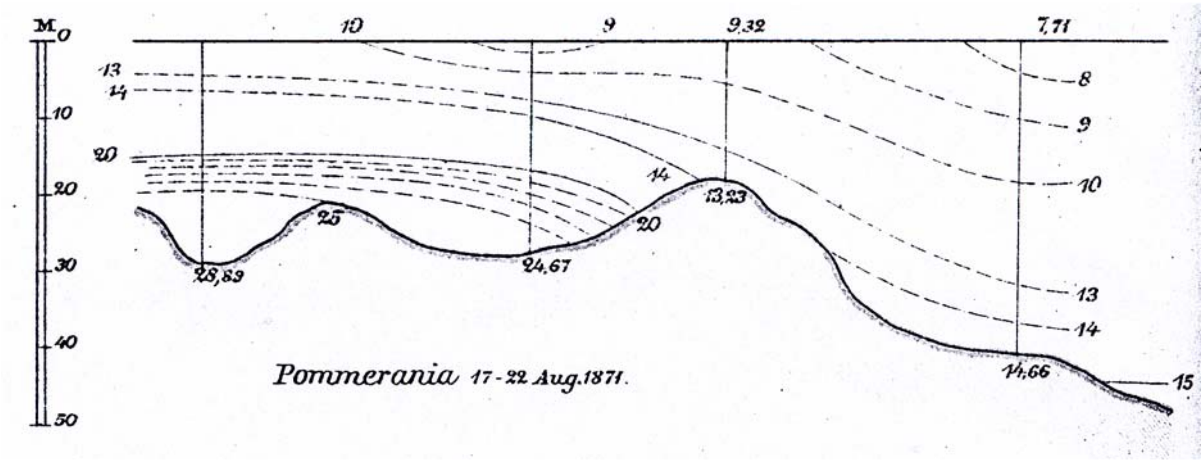

Fig. 3.1.
Longitudinal transect of salinity from the Fehmarn Belt to the Arkona Basin measured on board of the German steamer “Pommerania” in August 1871 (from PETTERSSON 1893, Table IV).

Abb. 3.1.
Längsschnitt des Salzgehaltes vom Fehmarnbelt zum Arkonabecken, gemessen auf dem deutschen Dampfer „Pommerania“ im August 1871 (aus PETTERSSON 1893, Tabelle IV).

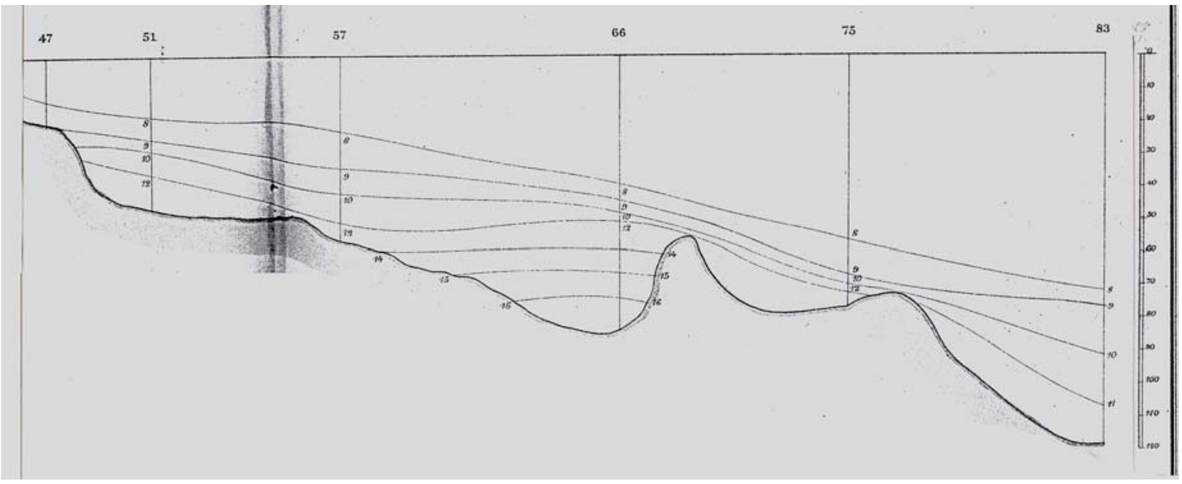

Fig. 3.2.
Longitudinal transect of salinity from the Darss Sill to the eastern Gotland Basin measured on board of the Swedish gunboat “Alfhild” in July 1877 (from PETTERSSON 1893, Table IV).

Abb. 3.2.
Längsschnitt des Salzgehaltes von der Darßer Schwelle bis ins östliche Gotlandbecken, gemessen auf dem schwedischen Kanonenboot „Alfhild“ im Juli 1877 (aus PETTERSSON 1893, Tabelle IV).

PETTERSSON published a lot of longitudinal and cross transects of temperature and salinity covering the whole Baltic Sea. Later he carried out gas analyses in order to determine the oxygen concentration in the deep water (PETTERSSON 1894).

Fig. 3.2 gives a longitudinal transect of salinity between Darss Sill and eastern Gotland Basin in July 1877 showing a pool of higher saline water in the Bornholm Basin (Stat. 66) and the inclination of the halocline in direction to the central Baltic. Based on the observations of the expedition PETTERSSON has reported on the propagation of the salty water penetrated into the Baltic during inflows:

> "…saltvatten sprider sig alltså med underströmmen från V. Östersjön genom rännan mellan Bornholm och Sverige till de tre stora undervattensbassinerna uti Östra Östersjön, nemligen Bornholmsdjupet Ö. om Bornholm, Gotlandsdjupet S. och Ö. om Gotland och Landsortsdjupet NV om Gotland" (PETTERSSON 1893, p. 102).

He wrote on the salinity of the water bodies transported downstream:

> "…underströmmen medfört vatten af öfver 16 ‰ salt till den yttersta bassinen Bornholmsdjupet samt något öfver 12 ‰ til den stora östra Gotlandsbassinen och 10 ‰ til vestra Gotlandsbassinen" (PETTERSSON 1893, p. 103).

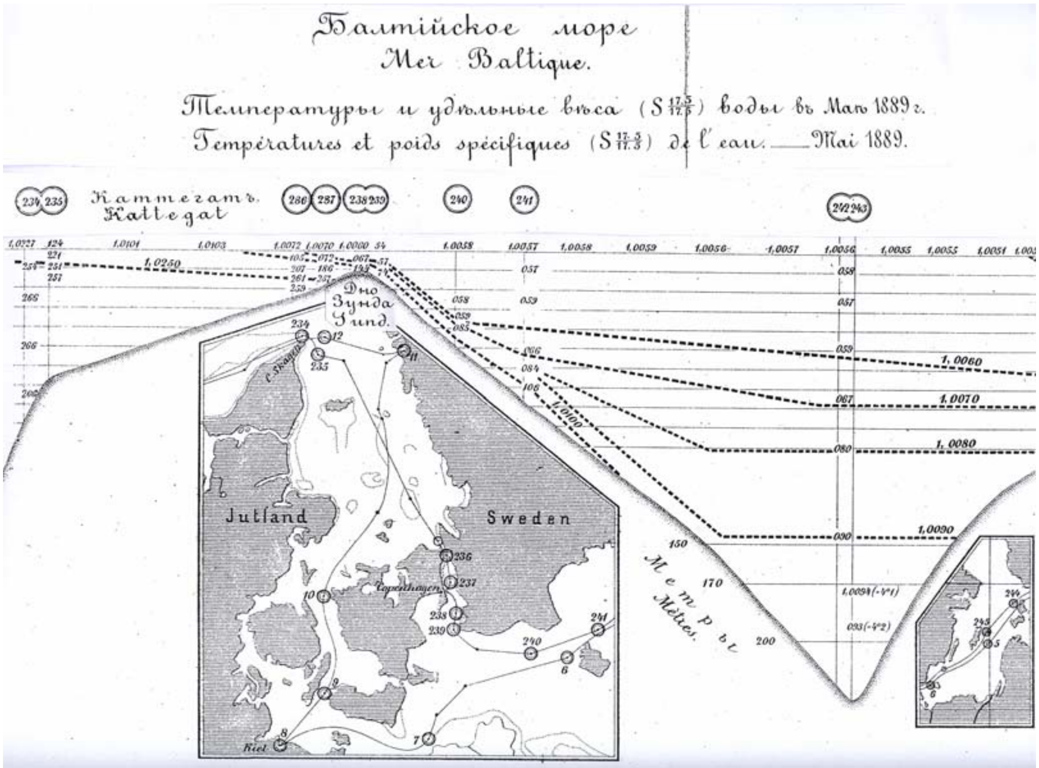

Fig. 3.3.
Longitudinal transect of specific gravity of the sea water from the Sound into the Baltic Sea measured on board of the Russian corvette "Vitiaz" in May 1889 (from MAKAROFF 1894, drawing XXIX).

Abb. 3.3.
Längsschnitt des spezifischen Gewichts des Meerwassers vom Sund in die Ostsee, gemessen auf der russischen Korvette „Vitiaz" im Mai 1889 (aus MAKAROFF 1894, Zeichnung XXIX).

The Russian admiral and oceanographer STEPAN O. MAKAROFF (1849 – 1904) made a contribution to the investigation of the Baltic oceanography in the second half of the 1880s. He circumnavigated the globe in the Royal Russian corvette "Vitiaz" in 1886-1889. During the voyage out from Kronstadt to Kiel in September 1886 and during the homeward journey from the Sound to Kronstadt in May 1889, he carried out oceanographic observations at 26 stations in the Baltic Sea (MAKAROFF 1894). During the return to Kronstadt in May 1889, he measured the specific gravity of the sea water from the Sound into the Baltic (MAKAROFF 1894, Vol. 1, p. 202 and drawing XXIX). Although the oceans were the main observation area of the "Vitiaz"-expedition and despite of only six stations he was courageous to draw an inflow of more saline water from the Sound downward into the Bornholm Basin (cf. Fig. 3.3), perhaps the effect of the moderate MBI in February 1889 (Q_{96} = 13.4).

4. International observation programmes during the first half of the 20th century

In1880, a large number of Danish and Swedish light vessels was established in the transition area between North Sea and Baltic (cf. e.g. NILSSON and SVANSSON 1974). This was the beginning of daily regular measurements of temperature and salinity in the off-shore area and formed the basis for the identification of salt water inflows into the Baltic Sea. The increasing number of coastal stations at the beginning of the 20th century, the international co-operation and the first international agreed periodic monitoring programme of the Baltic Sea, initiated by ICES in 1902, supported more intensive investigations on the pathway of the inflowing salt water and their effects in the central Baltic. Moreover, the basic methods for determination of temperature (reversing thermometer; cf. MATTHÄUS, 1968), salinity (MOHR-KNUDSEN-method) and oxygen content (WINKLER, 1888) were established and internationally accepted.

Based on monitoring results KRÜMMEL (1904) reported on the propagation of the water penetrated during the strong MBI in December 1902 (Q_{96} = 20.3; cf. No. 26 in Table 6.2) and on the renewal process in the Arkona, Bornholm and Gdańsk Basins between February 1903 and February 1904. The German chemist ERNST RUPPIN (1905) used the oxygen concentration of the water penetrated during Baltic inflow events for characterizing the renewal process in the central deep basins. Based on the German monitoring cruises between 1902 and 1904 he carried out analyses of dissolved gases and compared the variations in salinity, oxygen content and temperature of the bottom water of the Bornholm and Gdańsk Deeps (RUPPIN 1905). Later, KRÜMMEL used both the analyses of dissolved gases carried out by RUPPIN (1905) and the reported results of the monitoring cruises between 1902 and 1906 (ANONYMOUS 1903 – 1907) in order to describe the renewal in the Bornholm and Gdańsk Deeps between 1902 and 1906 (KRÜMMEL 1907).

JOHAN GEHRKE (1910) investigated in more detail the oceanographic conditions of the Baltic Sea based on the measurements of temperature, salinity and oxygen content during the first international periodic cruises between August 1902 and May 1907, which were decided to carry out by the ICES member countries. He has done the first detailed evaluation of the data set, which also included the effects of seven MBIs of the cluster 1901 – 1906 (cf. Fig. 6.2).

GEHRKE stated that the Kadet Channel is the main entrance for inflows into the Baltic but he assumed that the Drogden Sill is also of significance for the renewal of the central Baltic deep water. He identified the effects of the MBIs in 1901/1902 in particular of the strong inflow in January 1902 (Q_{96}= 27.7; cf. No. 12 in Table 6.2) into the central Baltic deep basins when cold water penetrated into the Gotland Deep.

GEHRKE stated

> "..Einströmungen in das Bornholmbassin vollziehen sich stossweise,..." (GEHRKE 1910, p. 103)

and that the Baltic deep water is mainly renewed by the conditions

> "…in den tieferen Schichten der Kadetrinne…, die bei ihrer stossweisen Einströmung in die Ostsee die salzige Unterlage...erneuern" (GEHRKE 1910, p. 7).

On the one hand, he thought that

> „…Salzwassereinströmungen in die Ostsee nicht an bestimmte Jahreszeiten gebunden sind…." (GEHRKE 1910, p. 107).

However, on the other hand, he wrote since

> "…die atmosphärischen Verhältnisse – die bekanntlich einen großen Einfluss auf die Einströmungen haben - ...im Sommer am ruhigsten sind, ...ist es sehr wahrscheinlich, dass die Einströmungen zu dieser Jahreszeit im allgemeinen nur verhältnismässig schwach sind. Dagegen…im Winter...werden die unruhigen Witterungsverhältnisse grosse Wassermassen in Bewegung setzen" (GEHRKE 1910, p. 108).

GEHRKE wrote:

> „…nur in seltenen Fällen ist das einströmende Wasser so schwer, dass es…das eigentliche Bodenwasser des Bornholmbassins erreicht." „Eine notwendige Bedingung hierfür ist…, dass das einströmende Wasser einen hohen Salzgehalt besitzt,…" (GEHRKE 1910, p. 107).

He already stated that variations in temperature of the bottom water of the Gotland Deep must be generated by water bodies which penetrated by

> "…stossweise horizontale(n) Einströmungen …" (GEHRKE 1910, p. 142).

However, he also found out that

> „..die Salzwassereinströmungen ...nicht immer warm zu sein brauchen." (GEHRKE 1910, p. 143).

Studies carried out by RUPPIN (1912) showed that

> „Im Bornholmbecken...das Bodenwasser" is renewed "in stärkerem Maße, als man früher geglaubt hat,...Die Erneuerung hat 2 Maxima, im Winter-Frühjahr und im Herbst." (RUPPIN 1912, p. 272).

The German oceanographer BRUNO SCHULZ (1888 - 1944) dealt with the ventilation of the North and Baltic Seas (SCHULZ 1924). On the mechanism of penetration of saline water into the Baltic and its propagation across the different basins, he stated:

> "…besonders infolge starker Nordweststürme…gelangt salzhaltigeres Wasser aus dem Kattegat und den dänischen Gewässern…über die trennenden Schwellen hinweg in das Arkonabecken...". „Ob dies Wasser aus dem Arkonabecken auf den Boden der Bornholmmulde gelangt oder eine Zwischenschicht bildet, hängt ganz von Temperatur und Salzgehalt des in der Unterschicht der Bornholmmulde bereits vorhandenen und des neu hineingelangenden Wassers ab" (SCHULZ 1924, p.109). „Das salzhaltigere, schwere Wasser der Unterschicht der Gotlandmulde..." originates from „der Unterschicht des Bornholm- und Arkonabeckens und damit dem Kattegat..." (SCHULZ 1924, p.110).

On the reduction in oxygen of the water flowing along the pathway from the Kattegat into the western Gotland Basin, he stated

> "…verschlechtert sich die Durchlüftung der Unterschicht…immer mehr auf dem Wege…rund um Gotland bis zur Schwelle zwischen Öland und der Mittelbank" (SCHULZ 1924, p.113).

In 1930, SCHULZ summarized the knowledge on water exchange between North Sea and Baltic in a general article in *Petermanns Mitteilungen* and wrote on the current conditions at the sills during strong inflows:

> "In beiden Zugangspforten zur Ostsee…kann die Einströmung erheblichen Umfang annehmen, wenn Luftdruck und Wind den Einstrom von Nordseewasser…begünstigen…Dann strömt schweres, salzhaltigeres Wasser "kaskadenartig" über die Schwellen hinweg…Am Südausgang des Sundes ist die Strömung dann vom Boden bis zur Oberfläche ostseewärts gerichtet, und häufig wird dies...auch über der Darßer Schwelle der Fall sein" (SCHULZ 1930, p. 189/190).

The chemical oceanographer KURT KALLE (1898 – 1975) – one of the German pioneers in marine chemistry - investigated the major turnover in the Gotland Deep in 1933/34 and brought about increased interest into the causes and conditions for major Baltic inflows (KALLE 1943). Based on measurements of temperature, salinity, oxygen and phosphate concentrations between 1926 and 1939 he investigated - for the first time - a long stagnation period (Fig. 4.1; cf. also salinity in Fig. 5.4) and described the turnover in 1933/34 in the Gotland Deep. He included phosphate into consideration and brought about increased interest into the significance of MBIs for the central Baltic deep water.

He stated: During the period

> "…(1934 – 1939) zeichnen sich die Bodenwasserschichten des Gotland-Tiefs durch eine...große innere Unruhe aus" (KALLE 1943, p. 145) (cf. also salinity and oxygen in Fig. 5.4).

This was caused by nine MBIs which FRANCK et al. (1987) identified for this period (cf. Fig. 6.2 and Table 6.2). Moreover, he suggested that these conditions will continue

> "…bis eine Wassermasse besonders großer Dichte die Tiefstlage über dem Boden einnimmt und damit zu einer Stabilisierung der Tiefenwasserschicht führt" (KALLE 1943, p. 145).

MANEGOLD (1936), KÄNDLER (1951) and WYRTKI (1954a) studied the weather conditions during inflow and outflow situations and the haline stratification in the transition area between the North Sea and the Baltic. Based on current observations at the light vessels in the transition area WALTER MANEGOLD (1936) investigated the weather conditions and the tracks of depressions during 300 cases of strong inflow and outflow events between 1901 and 1930. Most of the inflow situations occurred during autumn and winter reaching the peak in November and January. The inflow activity was lowest between May and July. This corresponds very well with the seasonal distribution of MBIs (cf. Fig. 6.2, upper right part).

In 1951, RUDOLF KÄNDLER (1899 – 1993) studied the interaction between various weather situations and the haline stratification in the transition area between the North Sea and the Baltic by means of the observations carried out on board of seven light vessels. He found:

> "If weather conditions are extremely favouring the inflow from the North Sea the vertical stratification almost completely vanishes and difference in salinity are observed only in horizontal direction" (KÄNDLER 1951, p. 151).

He showed such situations by means of the haline stratification during the strong MBIs in January/February (Q_{96}= 27.5; cf. No. 13 in Table 6.2) and October 1938 (Q_{96} = 22.6; cf. No. 22 in Table 6.2).

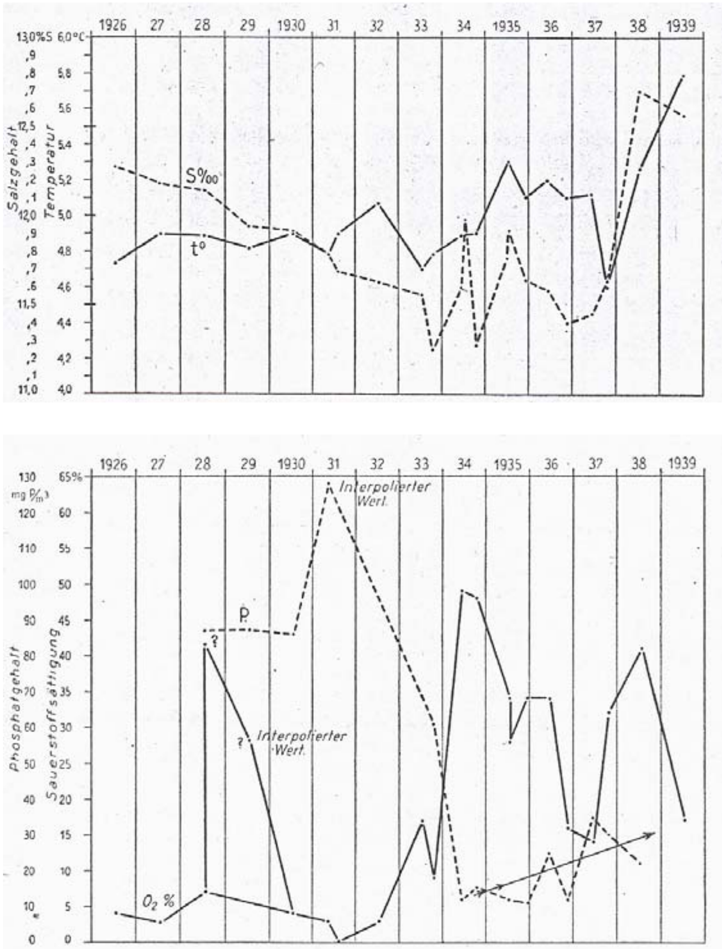

Fig. 4.1.
First long-term distribution of temperature, salinity, oxygen saturation and phosphate concentration in the 200 m level of the Gotland Deep (1926 – 1939) (from KALLE 1943, p. 145)

Abb. 4.1.
Erste Darstellung der Langzeitänderungen von Temperatur, Salzgehalt, Sauerstoffsättigung und Phosphatgehalt im 200 m Horizont des Gotlandtiefs (1926 – 1939) (aus KALLE 1943, S. 145)

WYRTKI (1954a) studied the typical processes of the water exchange between the North Sea and the Baltic in the transition area and characterized six inflow and outflow situations among them the inflow during persistent westerly gales. He investigated the dynamic processes (weather situation, sea level, currents, haline stratification) during the very strong MBI in 1951 (cf. chapter 5.1).

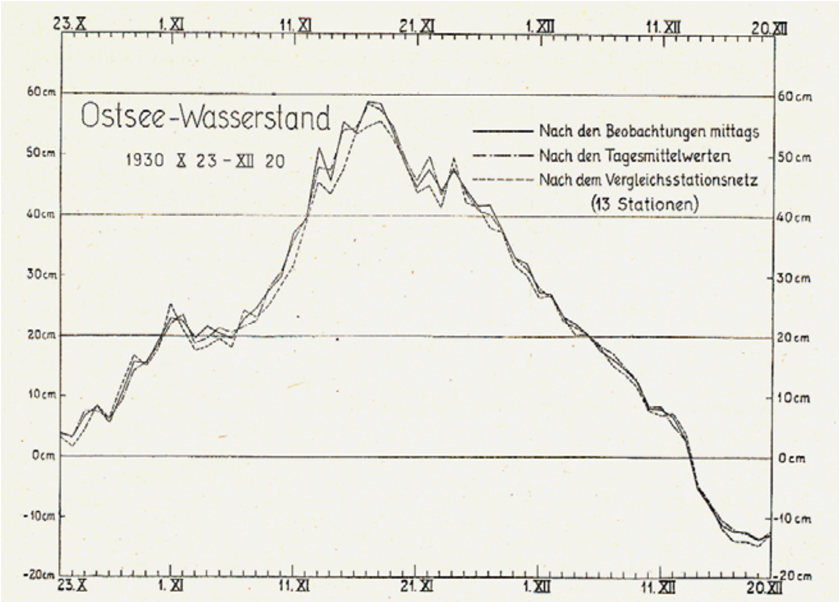

Fig. 4.2.
Variations of the mean Baltic sea level during the strong MBI in November 1930 (from HELA 1944).

Abb. 4.2.
Schwankungen des mittleren Wasserstandes der Ostsee während des starken Salzwassereinbruchs im November 1930 (aus HELA 1944).

The Finnish oceanographer ILMO Hela (1915 – 1976) studied the sea level variations of the Baltic between 1926 and 1935 in special consideration of the water exchange across the Danish Straits. Thirteen MBIs occurred during this period, among them two strong events. The highest sea level of this period was observed during the strong event in November 1930 (Q_{96} = 22.9; cf. No. 21 in Table 6.2). HELA (1944) documented the sea level rise before and after this MBI (Fig. 4.2). Owing to his studies there is the first detailed investigation of both the sea level variations and the currents in the Danish Straits before and during a MBI.

He supposed as main cause for the renewal of the central Baltic deep water the so-called

> "Grossaustausch", "…die pulsatorische, von meteorologischen Faktoren bedingte Strömung" (HELA 1944, p. 103).

With regard to the inflow process he stated:

> "Die Winde im Gebiet der Nord- und Ostsee verursachen…Strömungen in den dänischen Gewässern, die gewaltige Wassermassen in die...Ostsee verfrachten. Wenn die Strömung einwärts vor sich geht, bewegt sich die Beltseefront an der Oberfläche bis zu den Schwellen der Ostsee, wonach das schwere, salzreiche Kattegatwasser in die Tiefe der Ostsee sinkt....Das salzreiche Wasser bewegt sich unter Vermischung langsam weiter, und zwar infolge der ablenkenden Wirkung der Corioliskraft längs der südlichen und östlichen Küste der Ostsee" (HELA 1944, p. 99).

5. The analysis of selected events during the second half of the 20th century and their effects in the central Baltic deep water

5.1 MBIs in the 1950s and 1960

During the first half of the 20th century, Baltic oceanographers were occupied with the general investigation and description of both the exchange processes and the effects of salt water inflows in the Baltic Sea due to the lack of sufficient observation data. That changed after the major Baltic inflow in 1951, the strongest event observed so far. The interest in this special kind of water exchange increased considerably. Owing to the regular and frequent oceanographic observations and improvements in measuring techniques since the 1950s, more detailed investigations on mechanism and causes were carried out, mostly concerned with selected marked inflow events or the effects of MBIs on the deep water conditions.

In 1954, the German oceanographer KLAUS WYRTKI started detailed investigations of major Baltic inflows. In connection with his studies on the water movements in the Fehmarn Belt he analyzed the typical processes of the water exchange between North Sea and Baltic in the transition area and characterized six inflow and outflow situations among them the inflow situation during persistent westerly gales (WYRTKI 1954a). He also investigated the dynamic processes in the transition area during the exceptional strong MBI in November/December 1951 (Q_{96} = 51.7; cf. No. 1 in Table 6.2). In more detail, he analyzed course and oceanographic and meteorological causes of this MBI using current, salinity and sea level conditions and the depression tracks (WYRTKI 1954b). He documented the progress of the inflow event from 16 November to 21 December by means of salinity distributions between Kattegat and Darss Sill (Fig. 5.1).

WYRTKI has found that the coincidence of three important factors was decisive for the occurrence of the 1951 event:

- The MBI was
  "Grundsätzlich bedingt…durch eine drei Wochen lang anhaltende Westlage mit starken Stürmen."

- The precondition for the *amount* of penetrated water was
  "…der niedrige Wasserstand in der Ostsee und damit die vorangegangene anhaltende Ostlage."

- The precondition for the *strength* of the MBI was
  „...der hohe Salzgehalt in der Tiefe des Kattegats und sein weites Vordringen in die Belte." (WYRTKI 1954b, p. 24)

WYRTKI (1954b) tried to estimate the amount of water and salt which penetrated into the Baltic Sea during the 1951 event. Based on three different methods he found a volume of about 200 km^3, which penetrated between 23 November and 16 December 1951. He calculated that about 4.4 Gt salt were transported into the Baltic. His basic results on major inflows were included in German oceanographic handbooks (e.g. DIETRICH and KALLE 1957; DIETRICH et al. 1975).

The geographer and oceanographer RUDOLF SCHEMAINDA (1921 - 1987) studied the oceanographic variations in the Bornholm Basin after the very strong MBI in November/December 1951 based on observations of the German and Polish Fisheries Research Institutes (SCHEMAINDA 1957).

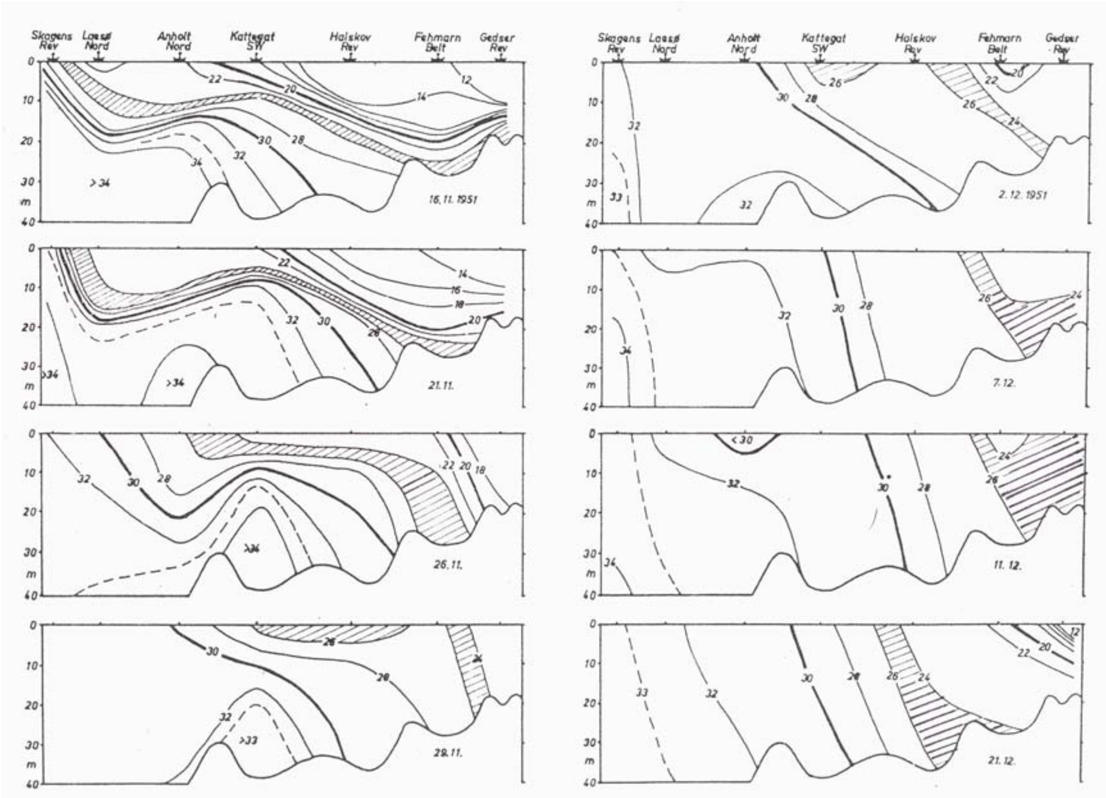

Fig. 5.1.
Longitudinal transects of salinity from l/v "Skagens Rev" to l/v "Gedser Rev" between 16 November and 21 December 1951 (from WYRTKI 1954b, Table 13)

Abb. 5.1.
Längsschnitte des Salzgehaltes vom Feuerschiff „Skagens Rev" bis Feuerschiff „Gedser Rev" zwischen 16. November und 21. Dezember 1951 (aus WYRTKI 1954b, Tafel 13)

In the 1950s, NIKOLAEV (1956), SOSKIN (1956, 1959) and SOSKIN and ROZOVA (1957, 1959) studied long-term variations of the thermohaline regime of the Baltic deep water and analyzed the connection of variations in temperature and salinity with the water exchange across the Danish Straits. SOSKIN (1963) summarized the results in a monography. He found out interactions between long-term variations of the thermohaline conditions, on the one hand, and variations in water exchange, river runoff, deep current and major Baltic inflows, on the other. He attributed these variations to large-scale changes in atmospheric circulation.

Based on the salinity data in the Baltic Deeps and partly on observations of temperature and oxygen in the Gotland Deep available to him, SOSKIN (1963) tried to identify major Baltic inflows. He could identify only roughly strong MBIs in 1934, 1938, 1948 and 1951. As we know today the variations which he observed in the deeps are caused by clusters of MBIs in 1934/35, 1938/39 and 1948 - 1952 (cf. Fig. 6.2) which included one moderate MBI in 1934 (Q_{96} = 18.9; cf. No. 32 in Table 6.2), two strong MBIs in 1938 (Q_{96} = 27.5 and 22.6; cf. No. 13 and 22 in Table 6.2), one moderate MBI in 1948 (Q_{96} = 19.6; cf. No. 29 in Table 6.2) and the exceptional strong MBI in 1951.

The Swedish oceanographer STIG H. FONSELIUS (1921 - 2003) has started the detailed description of the effects of MBIs in the central Baltic deep water (FONSELIUS 1962). He analyzed the long-term development of temperature, salinity and oxygen concentration in the Bornholm, Gotland and Landsort Deeps based on all data available up to 1961. He described in detail the stagnation period during the 1950s in the Gotland Deep and the effects of the MBIs in 1960 and 1961 (cf. also Fig. 5.4). However, he was not able to distinguish between the strong inflow in December 1960 (Q_{96} = 24.4; cf. No. 18 in Table 6.2) and the moderate one in March/April 1961 (Q_{96} = 12.7) because of the relative small number of measurements.

FONSELIUS (1962) started to identify MBIs recognized from long-term variations mainly of salinity in the Bornholm Basin. In spite of the relatively small number of observations he was able to identify a total of 11 MBIs between 1902 and 1961, additionally several smaller MBIs between 1926 and 1937. Generally, he was of the opinion

> "sometimes temperature is a better indicator…" but "still better than the temperature and the salinity values, the oxygen values show inflows and the stagnation periods" (FONSELIUS 1962, p.12).

Nevertheless, he could not distinguish between MBIs consecutive in a few months because of the incomplete observations of that time. He explained the role of the Bornholm Basin for the propagation of the highly saline water penetrated downstream into the Gotland Basin (cf. also chapter 8) and knew the drawback of identification of MBIs from variations in the Gotland Basin. He already stated:

> "It is not always possible to identify the salt inflows described…in the Bornholm Basin, because they may not reach this area" (FONSELIUS 1962, p.12).

He gave a first description of the dynamic processes between the Baltic deep basins during MBIs, the importance of the Bornholm Basin as buffer basin (cf. chapter 8) and the possibility of overflow of the eastern Gotland Basin in intermediate depths downstream into the Landsort Deep.

Very few measurements of inorganic phosphorus were carried out before 1957. FONSELIUS introduced the nutrient variations in the Baltic deep water, in particular of phosphate, into the discussion of the effects of MBIs because of the greater amount of data on phosphate since then (FONSELIUS 1962). For the periods from 1961 to 1966 (FONSELIUS 1967) and from September 1968 to January 1970 (FONSELIUS 1970), he carried out a detailed study on variations in the phosphate regime of the central Baltic deep water during the stagnation and the turnover caused by MBIs. Later FONSELIUS and NEHRING used nitrate, ammonium and silicate as additional indicators for the effects of MBIs in the central Baltic deep water.

The determination of hydrogen sulphide by the Methylene-blue method was already introduced in the late 19th century by FISCHER (1883). However, hydrogen sulphide in sea water was still identified qualitatively by smell up to the late 1950s. The Finnish oceanographer GUNNAR GRANQVIST (1932) reported on smell of H_2S in depths >200 m of the Gotland Deep in August 1931. In November 1960, FONSELIUS (1962) introduced the quantitative determination of H_2S by means of the Methylene-blue method into the Baltic water mass analysis. He mentioned the definition of hydrogen sulphide as "negative oxygen" in connection with the Baltic deep water analysis already in 1962 (FONSELIUS 1962) and proposed in 1969 to express hydrogen sulphide as negative oxygen equivalents for comparison purposes in figures (FONSELIUS 1969).

5.2 MBIs in the 1970s

In 1970, FONSELIUS began with the systematic identification of MBIs by means of variations in oceanographic parameters in the eastern Gotland Basin deep water between 200 m depth and bottom (FONSELIUS and RATTANASEN 1970). Mainly based on the increase in oxygen concentration but taking also into consideration variations in temperature, salinity and density, he identified a total of 13 MBIs between 1952 and May 1970, of 19 MBIs up to 1977 (FONSELIUS 1977), of 21 MBIs up to 1979 (FONSELIUS 1981, cf. Fig. 5.2) and a total of 24 MBIs up to 1984 (FONSELIUS 1985). That means he could recognize in the eastern Gotland Basin deep water more than 60 % of all MBIs identified at the entrance sills during that period. However, he could not detect those MBIs which were nearly completely trapped in the Bornholm Basin or which passed the eastern Gotland Basin in intermediate depths.

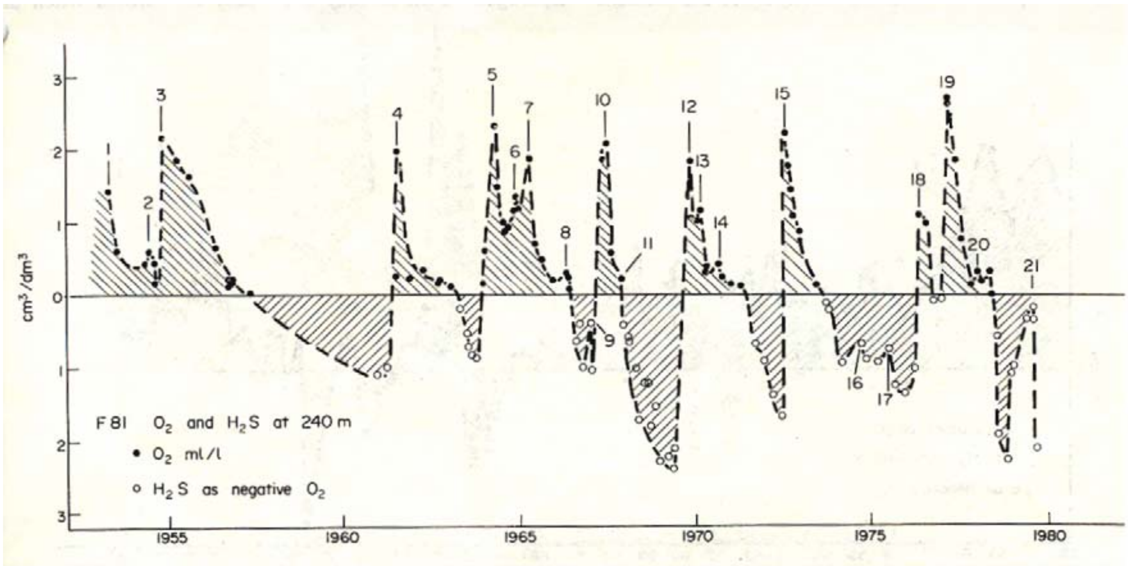

Fig. 5.2
Identification of MBIs by means of their effects on the oxygen concentration in the deep water of the Gotland Deep (from FONSELIUS 1981)

Abb. 5.2
Identifikation von Salzwassereinbrüchen an Hand ihrer Auswirkungen auf den Sauerstoffgehalt im Tiefenwasser des Gotlandtiefs (aus FONSELIUS 1981)

During the 1970s, the Institute of Marine Research in Warnemünde was mainly engaged in investigations of the effects of individual MBIs in the central Baltic deep water.

EBERHARD FRANCKE and DIETWART NEHRING (1971) studied the meteorological and oceanographic conditions which generated the MBI in February 1969 (Q_{96} = 13.2) (cf. also NEHRING and FRANCKE 1971). Later, NEHRING and FRANCKE (1973) described the effects of the MBIs of February and October/November 1969 in the central Baltic deep water. However, the effects of the MBI in autumn 1969 remained relatively small although it must be ranked among the strong events (Q_{96} = 29.2; cf. No. 9 in Table 6.2). The renewal process in the different basins is described by means of the variations in hydrographic and nutrient conditions (phosphate, nitrate, silicate). For the first time, the effect of a MBI in the central Baltic was studied in detail by a 5-day anchor station in the Gotland Deep in October 1969 (NEHRING et al. 1971). During the turnover process, a quick alternation between oxic and anoxic conditions was observed and considerable variations in chemical parameters were measured within three hours.

NEHRING and FRANCKE (1974) also studied the effects of the extreme inflow event in March/April 1972 which, however, did not reach the magnitude of a MBI. They concluded that inflow events of

> "...dieses Ausmaßes offenbar häufiger sind als ursprünglich angenommen wurde" (NEHRING and FRANCKE 1974, p. 32).

First information on the strong inflow event in 1975/1976 (Q_{96} = 25.6; cf. No. 15 in Table 6.2) was given by FRANCKE, NEHRING and BÖHL in June 1976 (FRANCKE et al. 1978). They reported on the current conditions at the permanent buoy station at the eastern slope of the Darss Sill, which was installed in 1973 by the Institute of Marine Research in Warnemünde (MÜLLER 1974, FRANCKE 1982). Moreover, they informed on the variations in oceanographic conditions of the central Baltic between autumn 1975 and April 1976. The inflow occurred over a period of four month interrupted by outflow periods. Strong inflow was observed from the end of September 1975 and reached peak

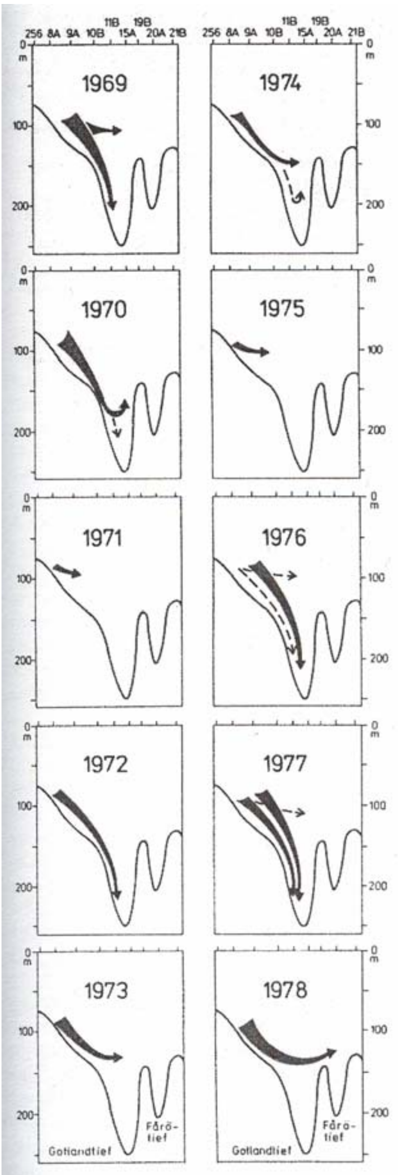

Fig. 5.3.
Schematic diagram of the inflow of saline water into the near-bottom and intermediate layers of the eastern Gotland Basin between 1969 and 1978 (from NEHRING und FRANCKE 1981)

Abb 5.3.
Charakterisierung des Einstroms salzreichen Wassers in die Boden- und Zwischenschicht des östlichen Gotlandbeckens zwischen 1969 und 1978 (aus NEHRING und FRANCKE 1981)

values in October and December 1975 and January 1976. A detailed description of the inflow event and its effects in the central Baltic deep water was given by NEHRING and FRANCKE (1978). In a summarizing contribution, NEHRING and FRANCKE (1981) published a schematic diagram of the inflows of saline water into the Gotland Basin between 1969 and 1978 (Fig. 5.3).

EBERHARD FRANCKE and PETER HUPFER (1980) studied current, wind, sea level and salinity conditions in the Darss Sill area during the major inflow event in 1975/1976. Based on measurements at the permanent buoy station they analyzed the currents in the surface and bottom layers in December 1975 and January 1976. HANS ULRICH LASS and REINHARD SCHWABE (1990) examined the dynamics of the mass and salt transports during a major Baltic inflow based on the strong MBI in 1975/1976. They found that the system Kattegat – Baltic Sea has a geostrophic controlled water exchange in the Belt Sea which linked the two sea areas. The advection of salt water through the Belt Sea occurs mainly in a river-like form without much exchange with water from the neighbouring bights.

NEHRING and FRANCKE (1980) reported on the inflow process at the second half of 1976 which culminated in a MBI in November/December 1976 (Q_{96} = 13) but they did not regard it as a major event. This inflow process caused an exceptional increase in temperature in the central Baltic deep water reaching more than 7 °C (FONSELIUS 1977, NEHRING and FRANCKE 1980, cf. also chapter 9).

FRANCKE and NEHRING (1986) dealt with the moderate MBIs in November 1982 (Q_{96}=13) and January 1983 (Q_{96}=12) the latest inflows before the start of the longest stagnation period ever observed in the central Baltic so far.

5.3 The very strong MBI in January 1993 and the warm water MBI in autumn 1997

The absence of effective inflows from the late 1970s to the early 1980s followed by a 10 years period without a major event (cf. Fig. 6.2) caused the longest and serious stagnation in the central Baltic deep water during the 20th century (Fig. 5.4). Therefore, Baltic oceanographers paid special attention to inflow events at the entrance sills to the Baltic since the 1980s. New measuring techniques and methods, the installation of permanent observations buoys and platforms in the sill areas and the Baltic Monitoring Programme (BMP) of the Helsinki Commission (HELCOM), which started in 1979, permitted a comprehensive and efficient monitoring both of the water exchange with the North Sea and the oceanographic conditions of the Baltic Sea.

Therefore, the MBI in January 1993 – an isolated event (cf. Fig. 6.2) - was subject to very intensive investigations. Owing to the large amount of data recorded by both land-based and ship-borne measurements (DAHLIN et al. 1993, HÅKANSSON et al. 1993, MATTHÄUS et al. 1993, JAKOBSEN 1995, LILJEBLADH and STIGEBRANDT 1996, PAKA 1996, ZHURBAS and PAKA 1997), this event provided a unique opportunity to carry out numerical analyses of the water and salt transports across the sills and the response of the downstream basins, to investigate the physical mechanisms (HÅKANSSON et al. 1993, JAKOBSEN 1995, LILJEBLADH and STIGEBRANDT 1996) and to do model simulations (HUBER et al. 1994, LEHMANN 1994a, 1994b, 1995). The International Council for the Exploration of the Sea devoted special theme sessions to the 1993 inflow event during its 81st and 82nd Statutory Meetings in 1993 (13 contributions) and 1994 (8 contributions).

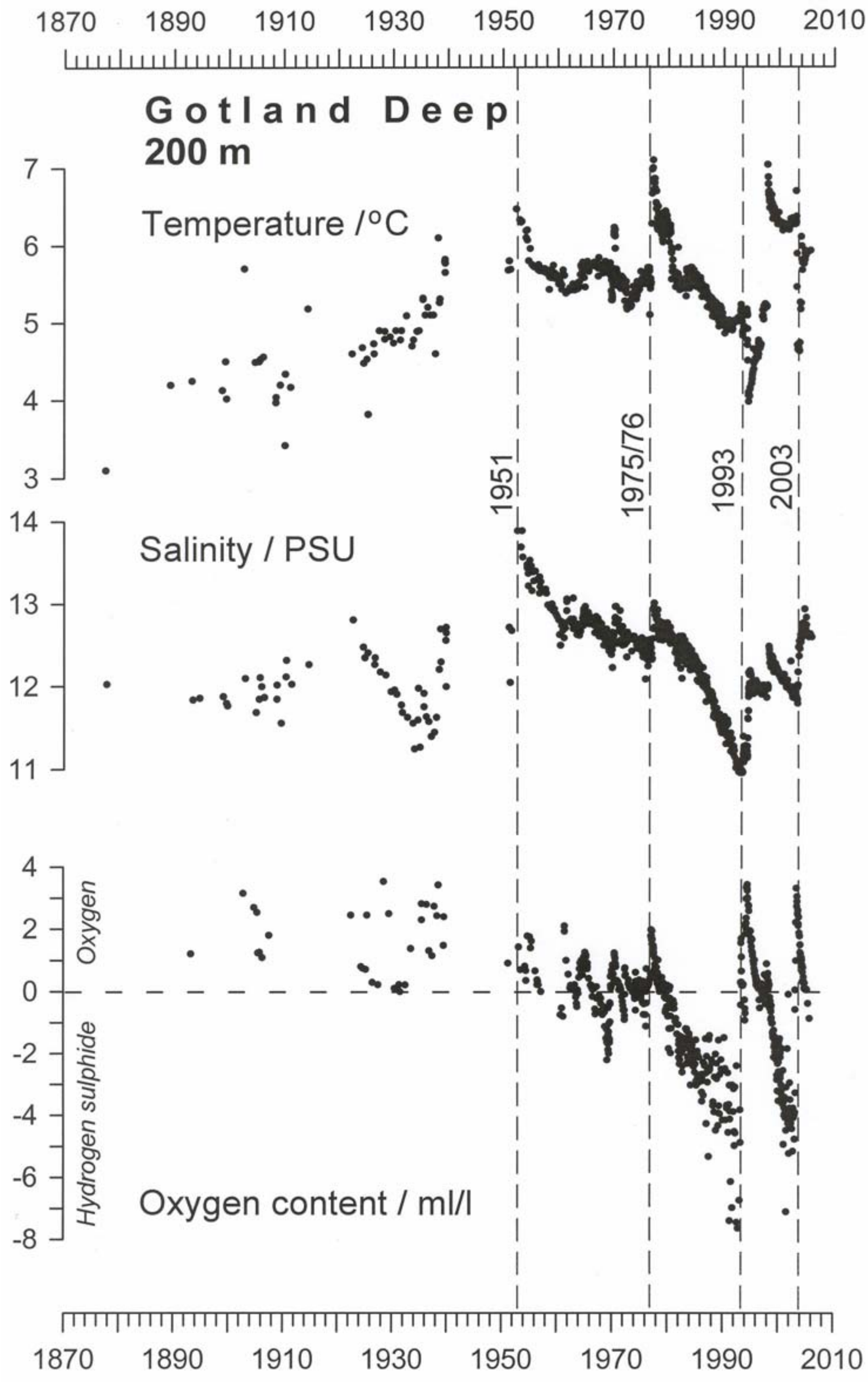

Fig. 5.4.
Long-term variations of temperature, salinity, oxygen and hydrogen sulphide concentrations in the deep water of the Gotland Deep (hydrogen sulphide converted into negative oxygen equivalents).

Abb. 5.4
Langzeitvariationen von Temperatur, Salzgehalt, Sauerstoff- und Schwefelwasserstoff-konzentration im Tiefenwasser des Gotlandtiefs (Schwefelwasserstoff als negative Sauerstoffäquivalente).

The 1993 event had another specific peculiarity: the Baltic sea level had raised already to more than +30 cm when the inflow of highly saline water started at the Darss Sill (MATTHÄUS et al. 1993, cf. also Fig. 6.4). Although the transport of water with salinities ≥17 PSU started at the Drogden Sill on 6 January (HÅKANSSON et al. 1993) the penetrated volume was relatively low (cf. Fig. 5.5A). An extended period of easterly winds at the end of 1992 and the first days of January 1993 lowered the Baltic sea level to about 20 cm below the long-term mean (cf. Fig. 6.4). This period was followed by a three-week phase of atmospheric depressions moving from the northeast Atlantic across southern Scandinavia. This situation produced uninterrupted strong westerly winds over the North Sea and the Baltic between 6 and 26 January, hurricanes occurred and passed through on 14, 22 and 24 January.

For the first time since investigations of MBIs began, the temporal development of the overflow across the sills and the filling up of the Arkona Basin with highly saline and oxygen-rich water has been comprehensively recorded (MATTHÄUS and LASS 1995, LILJEBLADH and STIGEBRANDT 1996). The Institute of Marine Research in Warnemünde studied the event by both an ADCP current meter and temperature-conductivity recorders in four levels moored at the Darss Sill (cf. Fig. 1.1B, Stat. 001). Moreover, a series of CTD casts was taken along a section crossing the Darss Sill into the Arkona Basin during the main inflow period between 20 and 28 January 1993 (Fig. 5.5). The Department of Oceanography in Göteborg carried out a hydrographic survey in the central and eastern Arkona Basin between 6 and 8 February 1993 using a CTD and a ship-borne ADCP for current measurements.

The inflow of highly saline water through the Sound across the Drogden Sill started immediately after the current changed direction and discharged highly saline water into the Arkona Basin (HÅKANSSON et al. 1993), where it forms a thin layer covering the bottom (cf. Fig. 5.5A). The thickness of this layer did not vary significantly between 21 and 28 January. The inflow of saline water into the Arkona Basin via the Great Belt was delayed by one to two weeks. The salinity at the Darss Sill exceeded 17 PSU on 18 January. The climax of the inflow at the Darss Sill occurred between 26 and 28 January. During the main inflow period, large amounts of highly saline water crossed the Darss Sill into the Arkona Basin. The primary halocline was lifted from 38 m to 10 m, and the 20 PSU isohaline was displaced from 42 to 32 m (Fig. 5.5B,C). There was an inclination of the halocline from the central Arkona Basin (25 – 30 m depth) to the Bornholm Channel (more than 40 m depth) (cf. LILJEBLADH and STIGEBRANDT 1996).

Despite the short duration, the amount of salt that flowed into the Arkona Basin was unusually large and caused an imbalance in the salt content in the basin leading to an uplifting of the halocline to above the level of the Darss Sill (cf. Fig. 5.5C). Hence, a relatively large amount of the salt flowed back into the Belt Sea and was lost for the renewal process in the central Baltic deep water. Nevertheless, the 1993 event has led both to a certain increase in salinity and, at least temporarily, to oxygenated conditions in parts of the central Baltic deep water (cf. DAHLIN et al., 1993; NEHRING et al., 1994).

ZHURBAS and PAKA (1997) analyzed the mesoscale and fine scale response of the eastern Gotland Basin to the 1993 MBI. In March/April 1993, they used a high horizontal resolution CTD profiling system in order to obtain CTD profiles with spacing of about 300 – 500 m between the Stolpe Channel and the Gotland Deep. The permanent halocline of the eastern Gotland Basin was influenced by intensive thermohaline intrusions and a cyclonic eddy. The eddy was likely generated by a nonstationary pulsed supply of the Bornholm water into the Gotland Basin (cf. also HAGEN and FEISTEL 2001). ZHURBAS and PAKA supposed that the combined effect of mesoscale eddies and thermohaline intrusions could be one of the mechanisms responsible for the deep water ventilation by MBIs.

Two smaller inflows of salt-rich water were recorded during winter 1993/1994 which, however, did not obtain the magnitude of major events. Because of the relatively high salinity in the Bornholm Basin deep water due to the 1993 MBI the buffer capacity of that basin was still exhausted (cf. chapter 8 and Fig. 8.2). The small inflows proceeded directly into the eastern Gotland Basin and caused changes which exceeded those after the MBI in January 1993. The oxygen content below 170 m depth reached the highest concentrations recorded since the 1930s (cf. Fig. 5.4; MATTHÄUS et al., 1994; NEHRING et al., 1995) and the 16 year of stagnation in the eastern Gotland Basin was finally terminated.

The 1993 event was rather unique with respect to to both the short duration of the total inflow process (22 days) and the large filling of the Baltic (70 cm above the mean water level). However, measurements and model results raised the question of the role played by the Drogden Sill compared to the Darss Sill regarding the saltflux. There were different estimations of the strength of the 1993 event. Using the Darss Sill data MATTHÄUS et al. (1993) considered the event as a moderate one (Q_{87} = 21.2; cf. MATTHÄUS 1993). HÅKANSSON et al. (1993) calculated that about

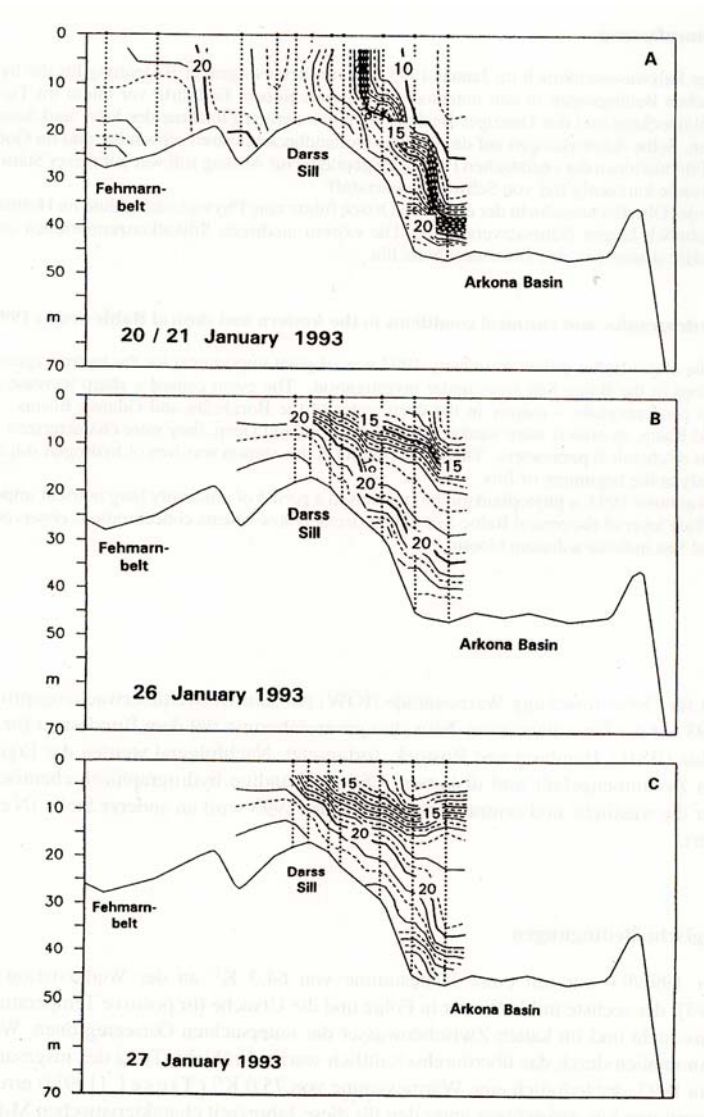

Fig. 5.5.
Longitudinal transects of salinity in the Darss Sill area during the MBI in January 1993 (from MATTHÄUS et al. 1993)

Abb. 5.5.
Längsschnitte des Salzgehaltes im Bereich der Darßer Schwelle während des Salzwassereinbruchs im Januar 1993 (aus MATTHÄUS et al. 1993)

50% of the total flow of highly saline water passed the Drodgen Sill into the Baltic Sea during the event. JAKOBSEN (1995) quantified the volume of highly saline water transported into the Baltic Sea directly from data measured in the Great Belt and the Sound. He estimated the 1993 event as very strong (Q_{87} = 34 ± 7). These discrepancies led to the re-assessment of the intensity of the MBI of January 1993 by FISCHER and MATTHÄUS (1996). The results showed that the event must be considered as a very strong one (Q_{96} = 34.0; cf. No. 5 in Table 6.2; cf. also chapter 6).

The part played by the Drogden Sill in the total event was the largest observed so far (FISCHER and MATTHÄUS 1996). The amounts of salt that crossed the two sills was almost equal.

Special attention was paid to the warm water inflow in autumn 1997 (MATTHÄUS et al. 1998, 1999, HAGEN and FEISTEL 2001) but the inflow was not recognized as MBI at that time. Using the amount of salt entering the Baltic Sea (FISCHER and MATTHÄUS 1996) the data at Darss and Drogden Sills were recently checked once more in order to find out whether the inflow in September 1997 must be regarded as a major event. The results show that the inflow must be added

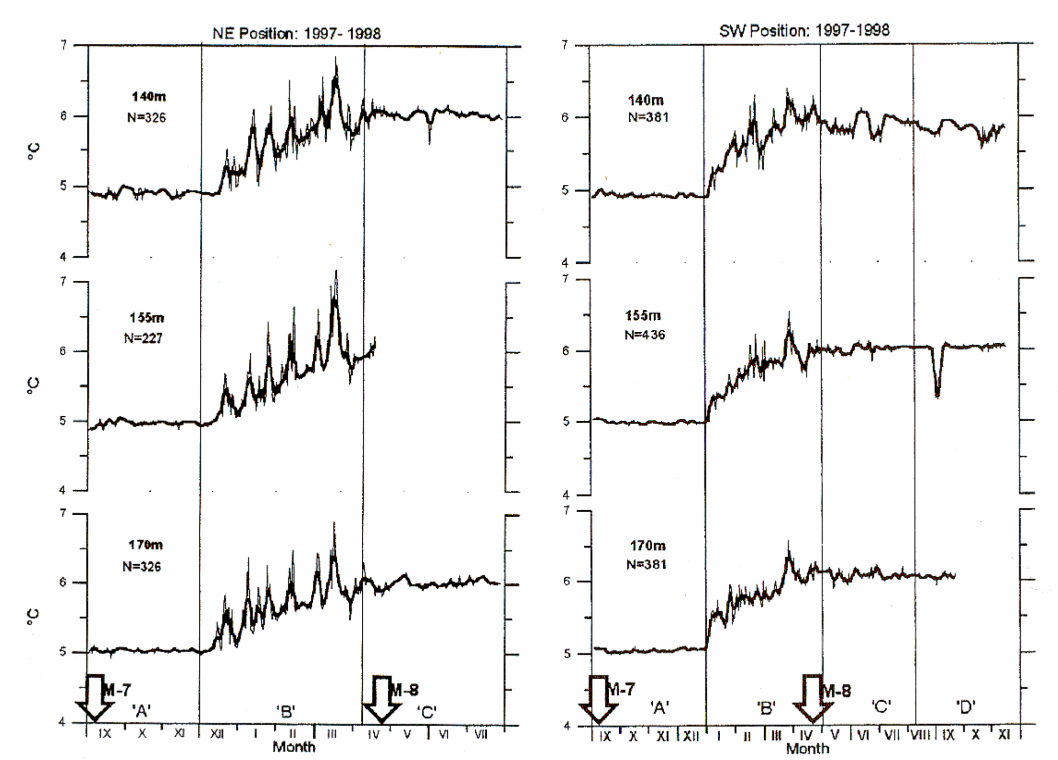

Fig. 5.6.
Temperature records at the 140 m, 155 m and 170 m level, measured at the south western and north eastern slope of the Gotland Deep during the warm water inflow between December 1997 and April 1998 (from HAGEN and FEISTEL 2001).

Abb. 5.6.
Temperaturregistrierungen im 140 m, 155 m und 170 m Horizont, gemessen am südwestlichen und nordöstlichen Hang des Gotlandtiefs während des Einstroms warmem Wassers zwischen Dezember 1997 and April 1998 (aus HAGEN and FEISTEL 2001).

to the series of MBIs. The inflow occurred at the Darss Sill between 15 and 21 September. Very warm and saline water passed both sills into the Baltic Sea (Darss Sill: mean salinity 17.9 PSU, temperature about 15 ^{o}C) and Drogden Sill (salinities: 18 - 27 PSU, temperature about 15 ^{o}C).

An intensity of Q_{96} = 11.2 was estimated, i. e. the MBI was a moderate one. The major amount of salt passed the Drogden Sill (Q_{DR} = 8.2) between 5 and 18 September. The part of the Darss Sill was only Q_{DS} = 3.0.

HAGEN and FEISTEL (2001, 2004) studied the dynamics of the water bodies in the central Baltic Sea during inflow events and stagnation periods. For the first time, they documented continuously the influence of a MBI (September 1997) on the deep water circulation in the deepest part of the eastern Gotland Basin – the Gotland Deep - by long-term records of two subsurface moorings (HAGEN and FEISTEL 2001). The moorings, installed at the topographic flanks in both the south-western and north-eastern part of the Gotland Deep at a depth of about 220 m, were equipped with recording current meters in 170 m depth and additionally with thermometers in 140 m, 155 m and 170 m. The inflow of the warm, saline and low oxygenated water started above the eastern slope of the basin in December 1997 and ended in April/May 1998 (Fig. 5.6). The current measurements revealed a mean cyclonic circulation following the bathymetric contours. The average duration of a complete cycle was estimated to be about 60 days along the 220 m isobath.The circulation lasted longer than one year. There is observational evidence that each new inflow pulse accelerated the ongoing deep circulation (HAGEN and FEISTEL 2001).

5.4 The specific MBI in January 2003

Ten years after the very strong MBI in 1993, another strong MBI occurred, again an isolated event (cf. Fig. 6.2). High pressure over Scandinavia associated with north-easterly winds at the beginning of January 2003 caused a mean filling of the Baltic of 20 – 30 cm below normal. On 11 January, the wind over the western Baltic increased to 15 m/s, turned to westerly directions and the sea level in the western Baltic suddenly fell to –80 cm resulting in a strong inflow. The inflow continued until 18 January at the Drogden Sill and until 22 January at the Darss Sill and the Baltic sea level rose to 25 cm above normal.

In the Sound, very high salinities were reported on 15 January (26.6 PSU, 2.5 ^{o}C) and 18 January (26.4 PSU, 2.2 ^{o}C). At the Darss Sill, salinities up to 21 PSU at the bottom and 18 PSU at the surface were measured. Using the measurements of salinity at the Darss and Drogden Sills, the inflow volume of highly saline water ($\geq$17 PSU) at the Drogden Sill and the increase in filling of the Baltic Sea, the MBI must be characterized as a strong one having an intensity of Q_{96} = 20.3 (cf. No. 25 in Table 6.2). The estimate of the salt transport across the Darss Sill was 1.18 Gt (~58 % of the total transport), that through the Sound 0.85 Gt (~42 %; cf. FEISTEL et al. 2003b).

The January 2003 event was a very specific one, never observed before. On the one hand, similar as the January 1993 MBI it was followed by weak inflows, not reaching the magnitude of a major event, in March and in May 2003. Both post-inflows enhanced the MBI because the Bornholm Basin was already filled with saline water and favoured the rapid eastward propagation into the central Baltic (cf. chapter 8). While the March inflow had almost the same temperature and oxygen content like the MBI the inflow in May was significantly warmer (5 – 10 ^{o}C).

However, on the other hand, two other weak inflows below the MBI category preceded the major event in January 2003, both supporting the effect on the deep basins by the MBI. The inflow in August/September 2002 (cf. chapter 9) was linked to exceptional weather conditions in late summer and possessed a strong halocline. It transported extremely warm water into layers at and below the permanent halocline. Although carrying only small amounts of oxygen, the water was capable of completely ventilating the Gdańsk Basin by November 2002 and reducing hydrogen sulphide concentrations even as far as the eastern Gotland Basin (FEISTEL et al. 2003c, FEISTEL et al. 2004a). The following shorter overflow of the Darss Sill in the first half of November 2002 was driven by westerly gales and carried well-oxygenated water (about 6 ml/l) with still rather high temperatures (about 10 ^{o}C) into the Bornholm Basin, replacing the bottom waters resting there during November.

Moreover, the large difference in temperature between the water penetrated during the MBI (down to 1.5 ^{o}C) and the ambient water originating from the exceptional summer inflow in 2002 (>10 ^{o}C) represented a unique opportunity to study both the propagation of the inflowing water and the mixing processes. The water moved very rapidly from the sills into the central Bornholm Basin (within 12 days at a speed of at least 30 cm/s; cf. PIECHURA and BESZCZYŃSKA-MÖLLER 2004).

The MBI in January 2003 and the temporal and spatial evolution of the Baltic deep water renewal has been investigated in detail by FEISTEL et al. (2003b). The event, the propagation of the saline and oxygen-rich water into the Baltic Sea and the ventilation of anoxic water between Bornholm Basin and central Baltic were recorded by the Darss Sill measuring mast, the Arkona Basin buoy, a subsurface mooring in the eastern Gotland Basin and several research cruises.

The response of the southern Baltic to the MBI in January 2003 has been documented by PIECHURA and BESZCZYŃSKA-MÖLLER (2004) showing frequent mesoscale structures and intensive mixing. During seven cruises between early December 2002 and mid-August 2003, the inflowing water was traced from the Arkona Basin to the Gdańsk Deep (cf. Fig. 1) by means of short-distant CTD casts, a towed CTD and a ship-borne ADCP. The penetrated saline water passed the western and southern slopes of the Bornholm Basin and formed a cyclonic eddy in the central part. In the central and western parts of the Bornholm Basin, the usual layering of temperature got a different spatial and temporal structure. The warm water residing between 60 and 90 m depth originating from the summer inflow in 2002 were replaced by cold water from the January MBI. By the end of April 2003 the new cold water mass reached the Gdańsk Deep, by generating patchy small-scale intrusions there.

6. The statistical analysis of MBIs

Between the 1970s and the 1990s, the cycle of water renewals had been well documented by the analysis of specific events (cf. chapter 5). Certain meteorological and oceanographic processes, however, determining the renewal in the central Baltic deep water were either not very well understood or even partly unknown. Therefore, the investigations started to focus on comparable measures for identification of MBIs and at the analysis of long-term series of the characteristics of the inflowing water.

The physical oceanographer GERHARD WOLF (1972) tried to analyze major Baltic inflows by means of a quantitative definition. His studies went back on investigations in the 1960s (WOLF 1966). Although he stated that extreme inflow events should be characterized as salt water inflows if that seems to be justified by the extent of the changes take place within the Baltic Sea, he suggested empirical criteria for identification of MBIs in the entrance area to the Baltic. He used the following criteria based on salinity observations at l/v "Gedser Rev" (GR) for identification of MBIs:

- ***GR 1:*** The stratification coefficient $G = S_o / S_b \cdot 100$ % (S_o = surface salinity, S_b = bottom salinity) at the Darss Sill must be ≥ 80 % for at least 5 consecutive days;
- ***GR 2:*** The bottom salinity S_b must be ≥ 17 PSU.

Based on the duration t of the inflow and the mean salinity S of the inflowing water he introduced an ordinal number r to estimate the ranking of MBIs according to their strength. In order to standardize the ordinal number to numerical values between 0 and 100 % WOLF classified an MBI with t = 5 days and S = 17 PSU with r = 0 % and t = 30 days and S = 24 PSU with r = 100 %.

Between 1950 and 1968, he identified 20 MBIs among them only two with an ordinal number r > 50% (cf. Table 6.1: r = Q_{72} in Table 6.2a). Moreover, he characterized the MBI of February 1969 (Q_{96} = 13.2) which was described in detail by FRANCKE and NEHRING (1971).

The promising attempt by WOLF (1972) was not followed up until the mid-1980s. In 1987, HERBERT FRANCK, WOLFGANG MATTHÄUS and RUDOLF SAMMLER started the statistical analysis of MBIs. They proceeded from the point that the amount and salinity of the inflowing water at the entrance sills to the Baltic characterize an inflow to be a "normal" one or a major event, independent from its effect in the central Baltic deep water. FRANCK et al. (1987) investigated - for the first time - a 80-year period from 1897 to 1976 using the daily salinity measurements at the l/v "Gedser Rev" (GR) in the Darss Sill area. The analysis was carried out by means of the general empirical criteria suggested by WOLF (1972)

- ***GR 1:*** The stratification coefficient $G = 1 - S_o / S_b$ at the Darss Sill must be ≤ 0.2 for at least 5 consecutive days;
- ***GR 2:*** The bottom salinity S_b must be ≥ 17 PSU.

but modified by specific criteria to decide whether or not single days before, after or between detected inflow events may be added to the inflow period. These criteria must be regarded as necessary to identify, but insufficient to quantify, the complete details of MBIs. The method permitted all MBIs to be detected during the period considered, and the determination of the exact date on which they started at the Darss Sill.

Table 6.1: Analysis of major Baltic inflows between 1950 and 1968 (from WOLF 1972)

Tabelle 6.1: Analyse von Salzwassereinbrüchen in die Ostsee im Zeitraum 1950 – 1968 (aus WOLF 1972)

Häufigkeit von Salzwassereinbrüchen in die Ostsee während der Jahre 1950—1968

Zeitraum	Zahl der Tage t [Tg.]	Mittl. Salzgehalt Oberfl./Boden $\overline{S}$ [‰]	Mittl. Schicht.-Grad $\overline{G}$%	Ordnungs-zahl r [%]
18. 2. bis 27. 2. 50	10	17,3	91,8	12,6
22. 9. bis 15. 10. 50	24	18,2	93,3	47,6
3. 12. bis 9. 12. 50	7	17,5	97,9	7,8
24. 11. bis 19. 12. 51	26	22,2	93,1	80,0
10. 1. bis 20. 1. 52	11	19,2	92,4	27,9
19. 11. bis 8. 12. 53	10	17,6	92,9	14,6
18. 1. bis 23. 1. 54	6	18,2	95,2	10,1
22. 9. bis 26. 9. 54	5	17,8	98,1	5,6
23. 12. bis 30. 12. 54	8	17,4	88,9	9,1
4. 12. bis 13. 12. 55	10	17,8	95,9	16,0
1. 1. bis 8. 1. 60	8	19,0	90,1	20,0
2. 12. bis 10. 12. 60	9	17,0	90,7	8,4
26. 3. bis 2. 4. 61	8	19,2	93,0	21,8
2.12. bis 11. 12. 61	10	24,1	95,4	60,0
20. 1. bis 25. 1. 62	6	20,2	95,5	24,6
4. 10. bis 18. 10. 63	15	18,9	87,4	34,4
18. 11. bis 28. 11. 63	11	17,3	92,6	14,9
5. 2. bis 9. 2. 64	5	17,5	86,7	1,8
15. 11. bis 30. 11. 64	16	18,7	91,5	34,9
30. 10. bis 5. 11. 65	7	18,3	92,5	13,2

FRANCK et al. (1987) characterized the identified MBIs by a relative intensity Q_{87} (cf. Table 6.2a), similar to the ordinal number introduced by WOLF (1972) but calculated by means of an empirical equation. Q_{87} is a function of the duration k_{GR} (in days) of the inflow and the mean salinity S_{GR} (in PSU) of the inflowing water:

$$Q_{87} = 50 \{(k_{GR} – 5)/25 + (S_{GR} – 17)/7\}.$$

Corresponding to this equation a MBI of k_{GR} = 5 days and S_{GR} = 17 PSU has an intensity of $Q_{87} = 0$. The intensity of $Q_{87} = 100$ characterizes an extremely strong MBI with k_{GR} = 30 days and S_{GR} = 24 PSU. FRANCK et al. (1987) also introduced a MBI classification scheme according to their relative intensity into weak ($Q_{87} \leq 15$), moderate ($15 < Q_{87} \leq 30$), strong ($30 < Q_{87} \leq 45$) and very strong ($Q_{87} > 45$).

They identified a total of 90 events between 1897 and 1976 (Fig. 6.1) during August and April, termed as *inflow season*. They distinguished between isolated major events, but most of them occurred in clusters separated by intervals from 1 to 4 years without MBIs (cf. Fig. 6.2). A cluster comprises all inflows separated by intervals of less than one year.

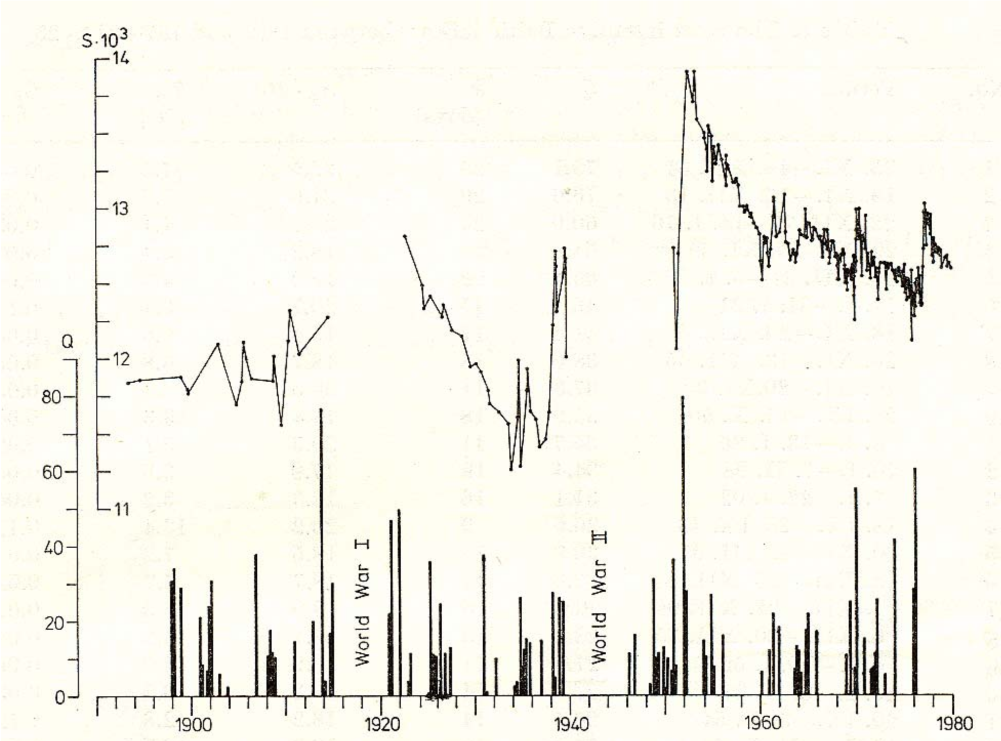

Fig. 6.1.
First diagramm of the intensity Q_{87} of the MBIs between 1897 and 1976 (below) and their effects on the salinity S in the 200 m level of the Gotland Deep (from FRANCK et al., 1987)

Abb. 6.1.
Erste Darstellung der Intensität Q_{87} der Salzwassereinbrüche zwischen 1897 und 1976 (unten) und deren Auswirkungen auf den Salzgehalt S im 200 m Horizont des Gotlandtiefs (aus FRANCK et al., 1987)

On the basis of decadal means and maximum values of salinity measured at l/v "Gedser Rev" MATTHÄUS (1995) estimated the MBIs between 1880 and 1896.

FRANCK et al. (1987) estimated the strength of MBIs by using the relative intensity Q_{87} as a function of the duration of the event and the mean salinity of the water penetrating across the Darss Sill. The role of the Drogden Sill for MBIs has been underestimated in the past. The significance of each sill varies considerably from event to event. The volume crossing the Drogden Sill during MBIs is, on average, one third of that crossing the Darss Sill and usually fare more salt enters the Baltic across the latter. However, in some cases, the amount of salt transported across the sills are equal or the amount crossing the Drodgen Sill is even the larger fraction.

Different estimations of the strength of the January 1993 event (cf. chapter 5) led to the re-assessment of the intensity. Instead of the mean salinity, HARTMUT FISCHER and WOLFGANG MATTHÄUS (1996) used the amount of salt q_S (in 10^{12} kg), entering the Baltic Sea both over the Darss (DS) and Drogden Sills (DR) as a criterion for the intensity of MBIs. They calculated the intensity on the basis of 90 events that took place between 1897 and 1976. The new method permitted – for the first time – the quantitative estimation of the strength of MBIs by using the total salt transport into the Baltic Sea.

In addition to the criteria GR 1 and GR 2 for identifying MBIs at the Darss Sill they used the following criteria to ascertain inflow days at the Drogden Sill belonging to each identified event:

- ***DR 1:*** The surface salinity S_o must be $\geq$ 17 PSU and the current must be directed into the Baltic Sea;
- ***DR 2:*** All (but not more than 15) days of the precursory and all days of the main inflow periods (see below), which meet condition DR 1, have to be taken into account.

The intensity of a major event corresponds to the amount of salt transported across the sills in water bodies with salinities $\geq$ 17 PSU. In order to standardize the intensity to numerical values between 0 and 100, FISCHER and MATTHÄUS divided the calculated amount by 10^{11} kg. The contribution of the Darss Q_{DS} and Drogden Sills Q_{DR} to the total intensity Q_{96} is:

$$Q_{96} = Q_{DS} + Q_{DR}$$

with $Q_{DS} = K_1\, q_{S,DS}$; $Q_{DR} = K_1\, q_{S,DR}$; $K_1 = 10^{-11}\ \mathrm{kg}^{-1}$.

They also adapted the MBI classification scheme introduced by FRANCK et al. (1987) to the re-assessed intensity Q_{96} into weak ($Q_{96} \leq 10$), moderate ($10 < Q_{96} \leq 20$), strong ($20 < Q_{96} \leq 30$) und very strong ($Q_{96} > 30$).

Major Baltic inflows identified between 1880 and 2005 shown in terms of the relative intensity Q_{96} and their seasonal distribution are given in Fig. 6.2. The characteristics of the 35 most intensive MBIs between 1880 and 2005 ranked according to Q_{96} are compiled in Table 6.2.

The water bodies penetrating into the Baltic Sea during MBIs have characteristic properties. Based on 90 events FRANCK et al. (1987) calculated temperature, salinity, oxygen content and density of the inflowing water and their seasonal variations (cf. also MATTHÄUS and FRANCK 1988). Seasonal variations of temperature and oxygen content were similar to those of the near-surface water between September and April with a temperature minimum and an oxygen maximum in February (Fig. 6.3). Hence, MBIs occurring between September and early December generally caused an increase in temperature of the Baltic deep water, whereas inflows from January to April led to a decrease. As far as the oxygen content is concerned the situation is reversed (cf. Fig. 6.3). More intensive MBIs in the first part of the inflow season generally did not have such marked effects on the oxygen conditions in the deep water as inflow events between January and April. Seasonal variations of salinity and density of the inflowing water were small (cf. MATTHÄUS and FRANCK 1988).

FRANCK and MATTHÄUS (1992) investigated the sea level conditions associated with MBIs. They described inflow processes linked to MBIs by two fundamental parts: the *precursory* and the *inflow periods*. The *precursory period* covers the time from the minimum Baltic sea level preceding a major inflow to the start of that event. It is characterized by the inflow of water with relatively low salinity across the Darss Sill whereas highly saline water can already pass through the Drogden Sill. The last 15 days of the precursory period immediately preceding a major inflow – termed *pre-inflow period* – are most important for describing the characteristic Baltic sea level variations associated with MBIs. The *inflow period* is characterized by the influx of highly saline water across both sills up to the maximum Baltic sea level during this event. The *precursory period* and the *inflow period* together form the *inflow interval* covering the complete inflow process.

Fig. 6.4 shows four examples for the rise of the mean Baltic sea level during precursory and inflow periods of the very strong MBIs in 1951, 1921/1922 and 1993 and the strong MBI in 1975/1976.

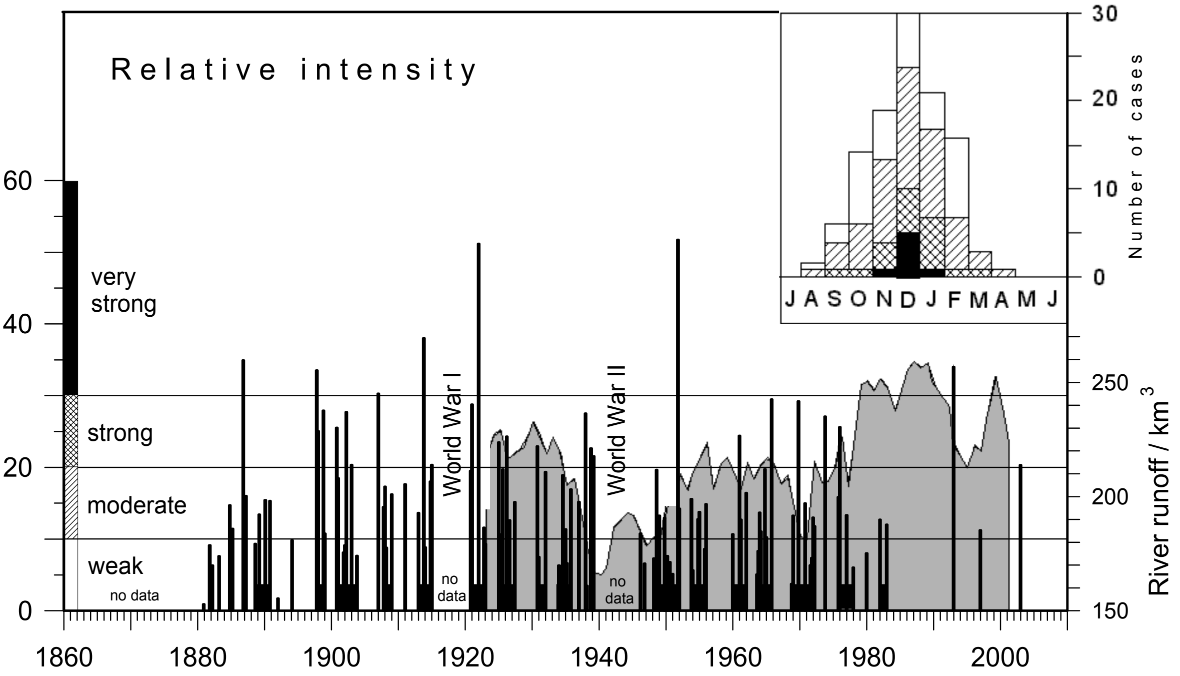

Fig. 6.2.
Major Baltic inflows (MBIs) between 1880 and 2005 and their seasonal distribution (upper right) shown in terms of their relative intensity Q_{96} (MATTHÄUS and FRANCK 1992; FISCHER and MATTHÄUS 1996; supplemented and updated) and five-year running means of river runoff to the Baltic Sea (inside the entrance sills) averaged from September to March (shaded). Black boxes on the time axis: MBIs arranged in clusters.

Abb. 6.2.
Salzwassereinbrüche in die Ostsee (MBI) zwischen 1880 und 2005 und ihre jahreszeitliche Verteilung (oben rechts), angegeben in relativen Intensitäten Q_{96} (MATTHÄUS and FRANCK 1992; FISCHER and MATTHÄUS 1996; ergänzt und aktualisiert) sowie 5-jährig übergreifende Mittelwerte der Flusswasserzufuhr zur Ostsee (innerhalb der Eingangsschwellen), gemittelt von September bis März (gerastert). Schwarze Felder auf der Zeitachse: Salzwassereinbrüche in Gruppen zusammengefasst.

Table 6.2a: The 35 most intensive Baltic inflows between 1880 and 2005 ranked according to their relative intensity Q_{96} (FISCHER and MATTHÄUS 1996).

Tabelle 6.2a: Die 35 intensivsten Salzwassereinbrüche zwischen 1880 und 2005, geordnet nach ihrer relativen Intensität Q_{96} (FISCHER and MATTHÄUS 1996).

No.	Main inflow period at the Darss Sill	MBI	Q_{96}	Q_{87}	Q_{72}
1	25 Nov – 19 Dec 1951	very strong	51.7	79.1	80.0
2	16 Dec 1921 – 6 Jan 1922		51.2	49.4	
3	18 Nov – 16 Dec 1913		38.0	76.6	
4	I.+ II. decade Dec 1886		34.9	52.3	
5	18 – 28 Jan 1993		34.0	21.2	
6	20 Nov – 4 Dec 1897		33.5	30.8	
7	26 Nov – 13 Dec 1906		30.3	38.0	
8	30 Oct – 8 Nov 1965	strong	29.5	16.9	13.2
9	29 Oct – 25 Nov 1969		29.2	54.8	
10	17 –31 Jan 1921		28.7	46.6	
11	7 – 22 Dec 1898		27.9	29.1	
12	7 – 22 Jan 1902		27.7	31.1	
13	24 Jan – 6 Feb 1938		27.5	27.3	
14	13 – 29 Nov 1973		27.0	41.4	
15	22 Dec 1975 – 14 Jan 1976		25.6	60.0	
16	18 – 28 Dec 1900		25.5	21.3	
17	20 Jan – 7 Feb 1898		25.0	34.4	
18	30 Nov – 10 Dec 1960		24.4	11.8	8.4
19	7 – 16 Mar 1926		24.3	24.5	
20	3 – 13 Jan 1925		23.5	35.7	
21	10 – 20 Nov 1930		22.9	37.3	
22	12 – 22 Oct 1938		22.6	25.9	
23	8 – 20 Feb 1939		21.5	24.9	
24	2 – 15 Dec 1914		20.3	30.0	
25	16 – 22 Jan 2003		20.3	14.1	
26	26 – 31 Dec 1902		20.3	6.2	
27	15 – 22 Nov 1964	moderate	19.7	17.5	34.9
28	3 – 9 Sep 1925		19.7	10.6	
29	18 – 26 Sep 1948		19.6	30.9	
30	14 – 25 Nov 1920		19.5	21.9	
31	26 Dec 1931 – 2 Jan 1932		19.4	9.9	
32	12 – 21 Oct 1934		18.9	25.9	
33	24 – 31 Jan 1901		18.5	8.6	
34	28 Sep – 8 Oct 1914		18.0	17.0	
35	26 Dec 1910 – 3 Jan 1911		17.6	14.7	

Q_{96}, Q_{87}, Q_{72} = relative intensity after FISCHER and MATTHÄUS (1996), FRANCK et al. (1987) and WOLF (1972);

Table 6.2b: Characteristics of the 35 most intensive Baltic inflows between 1880 and 2005.

Tabelle 6.2b: Charakteristische Eigenschaften der 35 intensivsten Salzwassereinbrüche zwischen 1880 und 2005.

No.	MBI	k_{GR} (days)	k_{DR} (days)	S_{GR} (PSU)	T_{GR} (°C)	O_{2GR} (ml/l)	S_{DR} (PSU)	V_{96} (km^3)
1	very strong	25	21	22.5	7.5	7.3	24.7	225
2		22	16	19.2	4.0	8.1	22.2	258
3		29	18	21.0	7.7	7.3	23.6	174
4		19		20.4				
5		9	22	18.7	3.5	8.2	25.2	159
6		15	11	18.5	7.2		21.3	177
7		18	18	18.7	6.8	7.6	23.1	151
8	strong	10	9	18.0	11.0		22.3	155
9		28	13	18.2	9.4	7.1	21.8	153
10		15	15	20.7	3.4	8.1	24.6	130
11		16	16	18.0	6.3		22.8	142
12		16	16	18.3	3.2		21.7	143
13		14	8	18.3	3.1		24.4	144
14		17	12	19.4	6.6	7.6	21.7	138
15		24	12	20.1	4.1	8.0	23.1	125
16		11	15	18.3	5.7		22.7	128
17		19	12	17.9	3.6		21.9	133
18		11	7	17.0	7.1		25.4	127
19		10	11	18.6	2.7		21.5	124
20		11	16	20.3	5.1		23.4	107
21		11	9	20.5	8.4	7.2	23.2	108
22		11	12	18.9	12.4		20.9	117
23		13	9	18.2	2.8		22.8	113
24		14	11	18.7	5.7		23.5	99
25		6	8	18.3	1.7		26.0	97
26		6	11	17.6	2.6		23.0	103
27	moderate	8	7	18.6	8.4		23.5	99
28		7	8	17.9	14.7		19.0	108
29		9	8	20.2	13.4		21.0	97
30		12	10	18.1	6.7		23.1	97
31		8	9	17.5	3.8		21.9	103
32		10	7	19.2	12.7		21.3	96
33		8	8	17.4	2.0		20.5	102
34		11	10	17.7	12.8		20.9	96
35		9	10	17.9	3.9		22.4	90

k = duration of the MBI; S, T, O_2 = mean salinity, temperature, oxygen content of the inflowing water; V_{96} = total inflow of water with S ≥ 17 PSU; GR = Gedser Rev; DR = Drogden Sill

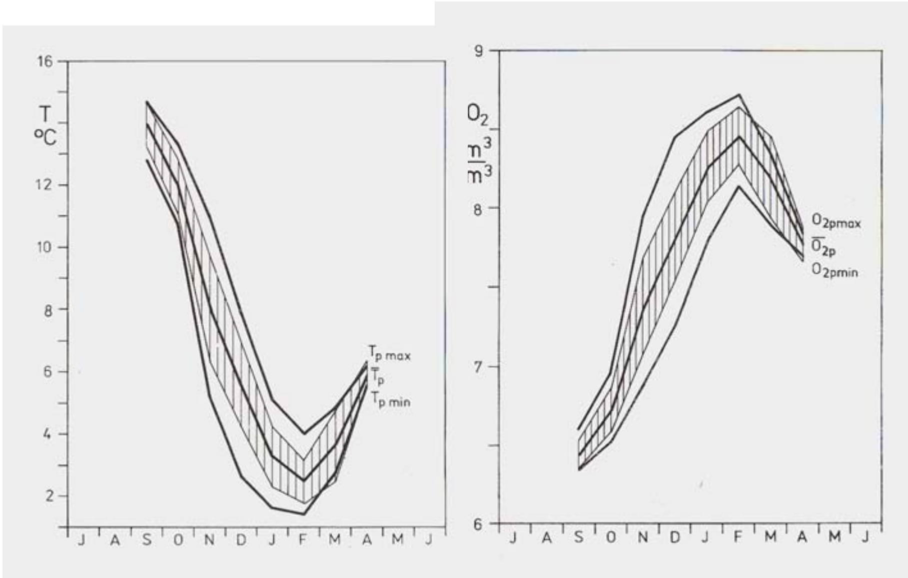

Fig. 6.3.
Seasonal variation of temperature T and oxygen concentration O_2 (monthly means and extreme values) of the water penetrating into the Baltic Sea during MBIs (from MATTHÄUS and FRANCK 1988).

Abb. 6.3.
Jahresgang von Temperatur T und Sauerstoffgehalt O_2 (Monatsmittel und Extremwerte) des Wassers, welches bei Salzwassereinbrüchen in die Ostsee eindringt (aus MATTHÄUS und FRANCK 1988).

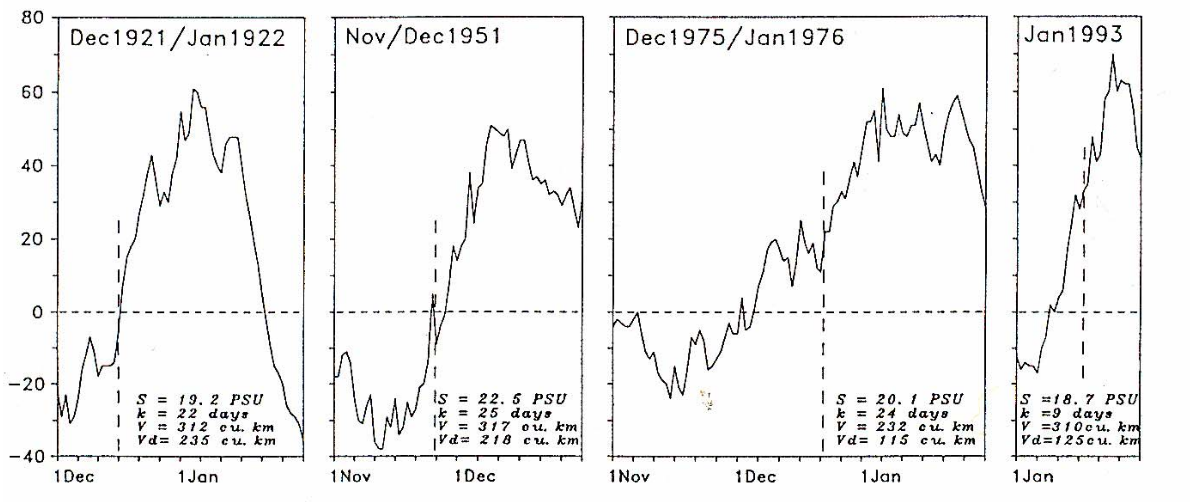

Fig. 6.4.
Rise of the mean Baltic sea level (station Landsort) during precursory and main inflow periods of selected strong and very strong MBIs (from MATTHÄUS 1993).

Abb. 6.4.
Anstieg des mittleren Wasserstandes der Ostsee (Station Landsort) während der Vorperiode und der Haupteinstromperiode von ausgewählten starken und sehr starken Salzwassereinbrüchen (aus MATTHÄUS 1993).

The lower part B of Fig. 6.5 shows the seasonal variations of the mean sea level of the Baltic Sea during years with and without MBIs. The mean sea level of the Baltic Sea is significantly lower from August to early November during years with MBIs than in years without MBIs.

Later, LASS and MATTHÄUS (1996) studied the wind conditions over the transition area and the sea level variation of the Baltic Sea in order to find characteristic sequences being associated with MBIs. Using the daily wind records at the meteorological station Arkona between 1951 and 1992 they could show that there is a remarkable difference in the zonal component in years with MBIs compared to years without major events. The westerly winds are significantly smaller between August and October in years with MBIs just before the strengthening of westerly winds (Fig. 6.5A; cf. also Fig. 8.1F). This is similar to the sequence observed in the annual cycle of the mean sea level of the Baltic Sea in years with MBIs, a lowering of the mean sea level between August and October precedes the increase of the sea level in November to December (Fig. 6.5B).

MATTHÄUS and FRANCK (1990) estimated the water volumes entering the Baltic Sea during MBIs and calculated the frequency distribution of the water volumes penetrating during the precursory and the inflow periods based on the 90 MBIs occurring between 1897 and 1976 (Fig. 6.6). The inflowing volumes for both parts of the inflow interval were estimated from the increase in the total Baltic water volume calculated from the Baltic sea level increase during each MBI. The volumes penetrating during the precursory period (predominantly between 80 and 160 km^3) originated mainly from the Belt Sea. The amount of highly saline water (≥17 PSU) entering the Baltic during the inflow period was generally smaller (Fig. 6.6b). MATTHÄUS and FRANCK (1990) stated that the volume of highly saline water is generally >100 km^3 during very strong MBIs and <100 km^3 during weak events. The total water volume penetrating during the inflow interval varied mainly between 140 and 220 km^3 (Fig. 6.6c).

The mean atmospheric circulation patterns associated with MBIs were investigated by MATTHÄUS and SCHINKE (1994). Based on a daily 5º x 5º grid point data set over the North Atlantic and Europe, they analyzed the mean sea level pressure field and the mean geostrophic wind conditions before, during and after the 87 MBIs identified between 1899 and 1976.

MBIs are mainly caused by strong zonal wind and pressure fields over the North Atlantic and Europe which vary little in direction. About two weeks before the start of the main period of a MBI, the Azores High shifts to north-east and its pressure increases. At the same time, the centre of lowest pressure moves eastward from the Greenland-Icelandic area to northern Norway, strengthening as it moves. Due to these movements, very strong pressure gradients occur over the North Sea and the entrance area to the Baltic. The maximum gradients were found two days before and on the first day of the main inflow event, respectively. Strong MBIs are characterized by higher pressure gradients than weak events. The stronger the inflow, the higher both the mean wind speeds and the duration of the strong wind period.

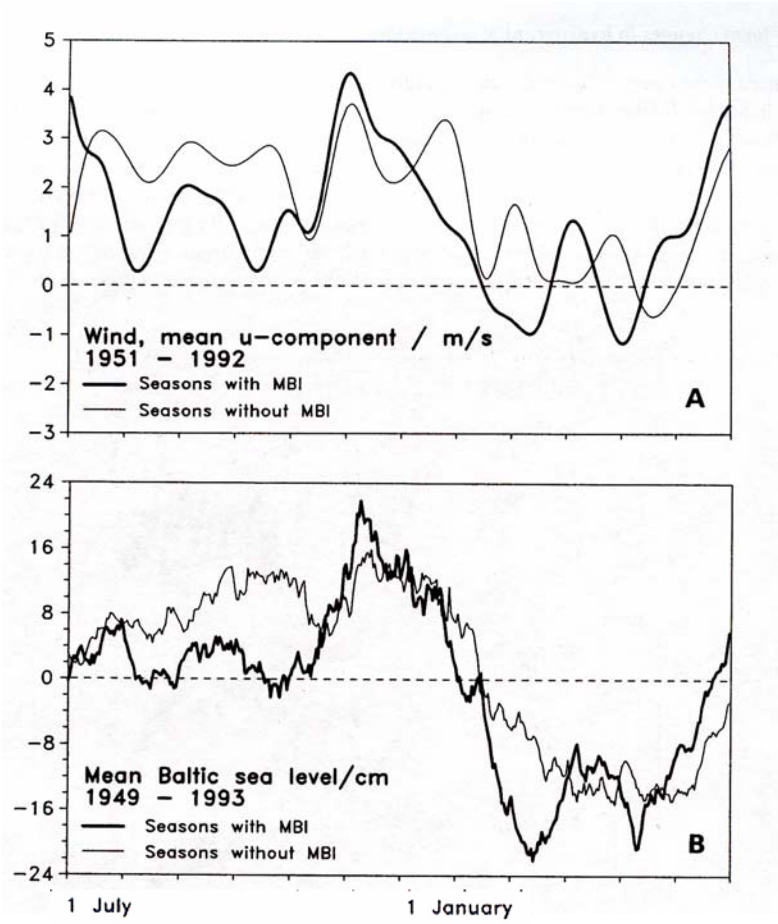

Fig. 6.5.
Annual variation of ensemble means of daily east component of the wind in the transition area (A; positive means wind from west) and of daily deviations from the 5-year running means of the Baltic sea level (B) for seasons with and without MBIs (from MATTHÄUS 1995).

Abb. 6.5.
Jahresgang der Mittelwerte der täglichen Ostkomponente des Windes im Übergangsgebiet (A; positiv: Wind aus West) und der täglichen Abweichung der 5-Jährigen gleitenden Mittel des Wasserstandes der Ostsee (B) in Jahren mit und ohne Salzwassereinbrüche (aus MATTHÄUS 1995).

Based on the data set of MBIs between 1897 and 1993 SCHINKE and MATTHÄUS (1998) investigated characteristic variations in meteorological, hydrological and oceanographic variables before and during major inflow events. They analyzed long time series of relevant variables from the Baltic Sea itself (salinity, sea level), its drainage area (river runoff, precipitation), the whole Baltic region (air temperature) and from the North Atlantic and Europe (sea level pressure) in order to identify conditions favouring or preventing such events.

SCHINKE and MATTHÄUS found out that MBIs are characterized by two phases: high pressure over the Baltic region with easterly winds (phase 1) followed by several weeks of strong zonal wind and pressure fields over the North Atlantic and Europe (phase 2). Major events may occur when only one of these is well developed, the probability of strong events is high if both phases are well developed and closely spaced in time. By comparison of inflow seasons without and with major events, conditions favourable for MBIs were found to occur between July and October (higher sea level pressure and salinity; lower wind speed from west, precipitation, Baltic sea level and river

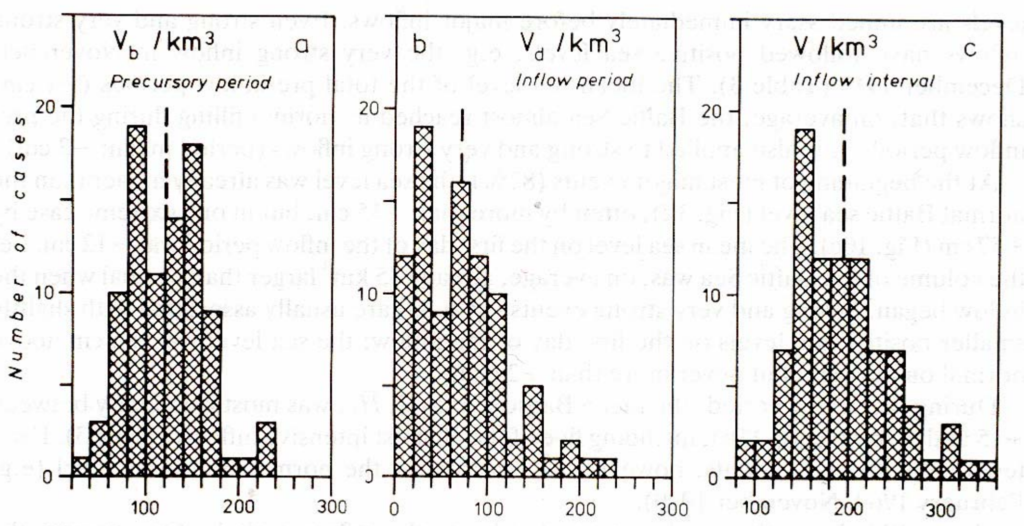

Fig. 6.6.
Frequency distributions of the water volumes penetrating before the beginning of the MBI at the Darss Sill (a), during the event (b) and during the complete inflow interval (c) (from FRANCK et al. 1987).

Abb. 6.6.
Häufigkeitsverteilungen der in die Ostsee einströmenden Wasservolumina vor Beginn des Salzwassereinbruchs an der Darßer Schwelle (a), während des Einbruchs (b) und während des kompletten Einstromintervalls (c) (aus FRANCK et al. 1987).

runoff). The differences are very distinct in October. Between November and April, significant differences could be found only in river runoff and salinity at the Darss Sill.

MBIs happened mainly during seasons characterized by lower runoff (cf. Fig. 6.2). Seasons identified by higher runoff have generally no MBI. Investigations by SCHINKE (1996) and MATTHÄUS and SCHINKE (1999) have shown that inflow seasons with higher runoff depending on higher precipitation correlate with persistent westerly winds in late summer and autumn. That resulted in an above-normal Baltic sea level by impediment of outflow from the Baltic and reduced the intensity of MBIs or completely prevents such events.

ZORITA and LAINE (2000) analyzed statistically the relationsship between the low-frequency (annually averaged) salinity and oxygen concentration in the Baltic Sea and the large-scale atmospheric circulation. The results showed that stronger westerly winds causes increased precipitation in the Baltic Sea catchment area and increase runoff giving rise to decreased annual salinities at all depths. Stronger zonal atmospheric circulation also enhances the oxygen concentration. The authors think that could be related either to a weakened stratification through the reduced salinity (at long time scales) or by stronger or more frequent MBIs (at short time scales). Increased precipitation and runoff associated with more intensive zonal circulation could reduce the inflows of oxygen-rich water. That has been also suggested by STIGEBRANDT (1983), SAMUELSSON (1996), SCHINKE and MATTHÄUS (1998) and MATTHÄUS and SCHINKE (1999).

7. Investigation of the causes of MBIs

The earliest information on the causes of penetration of salty water into the Baltic Sea go back to the beginning of the 19th century. Already CATTEAU-CALLEVILLE (1815) thought that the winds, especially from south and south-west, cause the transport of salt into the Baltic (cf. chapter 2.1).

Later, the undercurrents in the Belts and the Sound generated by wind were detected (FORCHHAMMER 1858). The winds strengthen or weaken the undercurrent of salt water into the Baltic (MEYER 1871). He stated that the transport of salt into the Baltic Sea is influenced - among others - by the effect of the wind on the Baltic sea level and the current speed. Moreover, MEYER already distinguished between different intensities of the inflow caused by the wind conditions.

KRÜMMEL (1895, 1904) and KNUDSEN (1900a) described the basic mechanism of the inflow of salt water and the renewal of the central Baltic deep water (cf. also chapter 2.2). Already KNUDSEN (1900b) found out that the inflow of salty water into the Baltic is about half the amount of the outflow. He also realized that salt water inflows occur intermittent (KNUDSEN 1900a).

Based on the analysis of the exceptional strong MBI in November/December 1951 WYRTKI (1954b) found the coincidence of three important factors to be decisive for the occurrence of MBIs. MBIs are caused by prevailing westerly wind with strong gales. Easterly winds over the Baltic Sea lowering the Baltic sea level are a precondition for the amount of penetrated salt water. However, WYRTKI thinks that high salinity of the Kattegat deep water and its further penetration into the Belts is a decisive precondition for the strength of a MBI (cf. also chapter 8).

The British oceanographer ROBERT R. DICKSON (1971) has shown, that during the 20th century the salinity in the north-western European shelf seas (English Channel, Irish Sea, North Sea) has fluctuated fairly regularly between periods of low and high values. Conditions of high salinity having peaks about every 3 – 4 years

> "…are shown to be associated with the periodic re-establishment over the North Atlantic sector of an anomalous and persistent atmospheric circulation pattern." (DICKSON 1971, p. 97).

Increased northern transport of salt

> "…induced in the eastern Atlantic by this circulation pattern…are held to be primarily responsible for each sustained salinification of these seas;…" (DICKSON 1971, p. 97).

According to DICKSON the occurrence of MBIs tends to coincide to a large extent with the end of the rise in the salinity of the shelf seas. He concluded that local meteorological conditions over Northern Europe and the Baltic itself can assist or retard the strength of the inflows, but he thinks they are unlikely to be capable of acting as primary causes of major inflows.

Based on this hypothesis DICKSON (1973) developed an informal attempt for prediction of MBIs. He has shown that

> "...in the post-war period, each inter-annual salinity maximum in the deep water of the Skagerrak has been accompanied by inflow to the Baltic, and although the hydrographic record from the Baltic deep basins is less detailed in earlier years, it is sufficiently good in the inter-war period to show a similar concurrence of events." (DICKSON 1973, p. 97).

Relevant meteorological and oceanographic time series have been subjected to spectral analyses and anomaly calculations to identify characteristic correlates with major events (BÖRNGEN 1978, 1983, BÖRNGEN et al. 1990, HUPFER et al. 1994). They found that the absence of MBIs since the mid-1970s could be attributed to variations in the meridional circulation over the North Atlantic, whereas the quasi-regular occurrence seems to be connected with the existence of a three-year oscillation of the meridional circulation.

MICHAEL BÖRNGEN (1978) estimated energy and coherence spectra of salinity at the 15 m level of l/v “Lappegrund” and “Gedser Rev”, meteorological (meridional circulation over the North Atlantic, zonal circulation over the Baltic) and oceanographic factors (Baltic sea level). Later he included further meteorological and oceanographic parameters and used the factor analysis and band-pass filtering (BÖRNGEN 1983). The analyses performed yielded evidence of a period of three years, especially since 1930, in the 15 m level salinity, in the meridional (North Atlantic) and zonal circulation (Baltic) and in the sea level. These results are in fairly good agreement with the correlation found by DICKSON (1971, 1973).

BÖRNGEN, HUPFER and OLBERG (1990) analyzed the long-time data sets used by BÖRNGEN (1978, 1983) by spectral correlation applying the Fast Fourier Transformation. They found distinct relationships in the period range of about three years. They thought that the occurrence and strength of MBIs seem to be determined by corresponding temporal variations in the meridional (North Atlantic) and zonal component (Baltic sea region) of the atmospheric circulation and of the Baltic sea level. That could be confirmed by the determination of the maximum-entropy spectrum for the salinity at the 15 m depth of the two l/v “Lappegrund” and “Gedser Rev” and the meridional circulation over the North Atlantic. A maximum-entropy spectral analysis was carried out in order to find out temporal changes of the spectral behaviour of the two time series (Fig. 7.1).

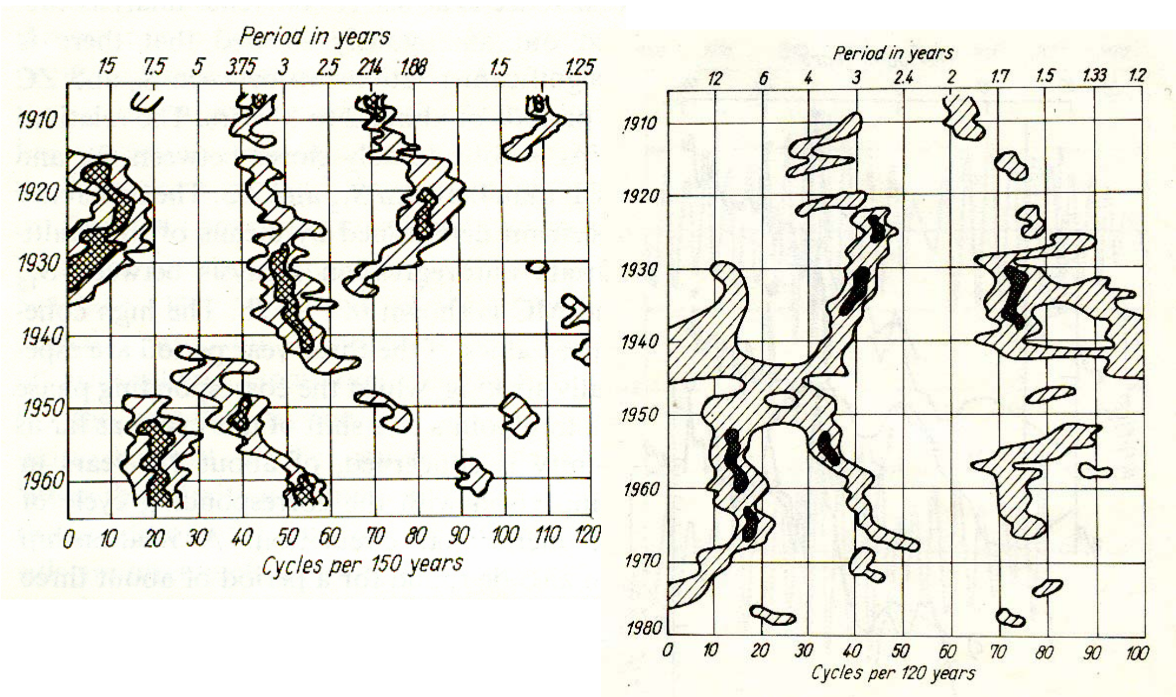

Fig. 7.1.
Maximum-entropy spectrograms of the time series of salinity at the 15 m level of l/v “Lappegrund” (left) and of meridional circulation over the North Atlantic (right) (hatched: significant areas) (from BÖRNGEN et al. 1990).

Abb. 7.1.
Maximum-Entropie-Spektrogramme der Zeitreihen des Salzgehaltes im 15-m-Horizont des Feuerschiffs „Lappegrund“ (links) und der meridionalen Zirkulation über dem Nordatlantik (rechts) (schraffiert: signifikante Bereiche) (aus BÖRNGEN et al. 1990).

Investigating the mean atmospheric circulation patterns MATTHÄUS and SCHINKE (1994) studied the “static” element of the circulation in causing MBIs. They could show that there are typical circulation patterns which trigger MBIs and are necessary for their occurrence. One of the basic conditions linked to major events is, on average, a mean continuous increase in wind speed from westerly directions over several weeks as, for instance, very distinctly observed in 1951 (WYRTKI 1954b) and 1993 (MATTHÄUS and LASS 1995). This increase begins about two weeks before the start of the main inflow period and reaches maximum values on the day before the overflow of water with salinities ≥17 PSU across the Darss Sill. The stronger the inflow, the higher both the mean wind speed and the duration of high wind speeds during the main inflow period.

While this fact represents the large-scale conditions forming the guideway for quickly passing depressions the "dynamic" element consisting of the sequence of depressions moving over the area represents the local conditions as causal factors of MBIs.

Further detailed investigations on the causes of MBIs were carried out by SCHINKE (1996). The results showed that MBIs can be characterized by two phases: During the first phase, favourable preconditions existing for one or two month (most commonly in September and October) before the event starts: High pressure with easterly wind over the Baltic region causes below-normal Baltic sea level and reduces both precipitation and river runoff. During the main phase, several weeks of strong zonal wind and pressure fields over the North Atlantic with generally only small fluctuations in direction cause the inflow of large volumes of highly saline water and lead to a rapid rise in Baltic sea level. The results showed that the decrease in frequency and intensity of MBIs since the mid-1970s and the complete absence of such events between February 1983 and January 1993 (cf. Fig. 6.2) can probably be attributed to increased zonal circulation. That results in both intensified precipitation in the Baltic region and increased river runoff (cf. also SCHINKE and MATTHÄUS 1998). These results were confirmed by model simulations carried out by MEIER and KAUKER (2003).

SCHINKE and MATTHÄUS (2003) studied periodic fluctuations in major inflows and characteristic anomalies in sea level pressure field over the North Atlantic and Europe preceding MBIs in order to identify teleconnections favourable for the occurrence of MBIs. Their results have shown that the various anomalies identified in the sea level pressure field up to three years preceding a season with MBIs seem to have no influence on their occurrence. In contrast to the investigations carried out by BÖRNGEN et al. (1990) close connections between variations of the meridional circulation over the North Atlantic and the occurrence or absence of MBIs could not be found. Favourable conditions for the occurrence of MBIs seem to be almost exclusively generated in the Baltic Sea area itself.

8. On preconditions for the occurrence of MBIs

WYRTKI (1954b) analyzed the very strong MBI in 1951 and found out that the event was caused – among others - by three week lasting westerly winds connected with strong gales. MATTHÄUS and SCHINKE (1994) studied in detail the mean atmospheric circulation patterns associated with the 87 MBIs identified between 1899 and 1976 and confirmed that a strong zonal circulation between the central North Atlantic and eastern Europe with only small fluctuations in wind direction over the transition area is a necessary precondition for MBIs. One of the basic conditions linked to the occurrence of MBIs is a mean increase in wind speed from westerly directions over several weeks.

The question for the role of the filling state of the Baltic Sea for the occurrence of MBIs was already raised by WYRTKI (1954b). He considered a low Baltic sea level with preceding easterly winds as a precondition for the *amount* of water penetrating during MBIs. LASS and MATTHÄUS (1996) could show that there is a lowering of the mean Baltic sea level between August and October of years with MBIs compared to years without MBIs (cf. Fig. 6.5).

Investigating weather situations favourable for major inflows SCHINKE and MATTHÄUS (1998) calculated mean monthly anomalies of sea level pressure fields in seasons without and with MBIs. The results showed that the occurrence of high-pressure areas over the Baltic from late summer to autumn is very favourable for MBIs. The large anomalies over the Baltic region in October (negative in seasons without MBIs: -3.3 hPa, cf. Fig. 8.1E; positive in seasons with MBI: +1.3 hPa, cf. Fig. 8.1F) are the most obvious. Anomalies are also recognizable in August and September (cf. Fig. 8.1A – D).

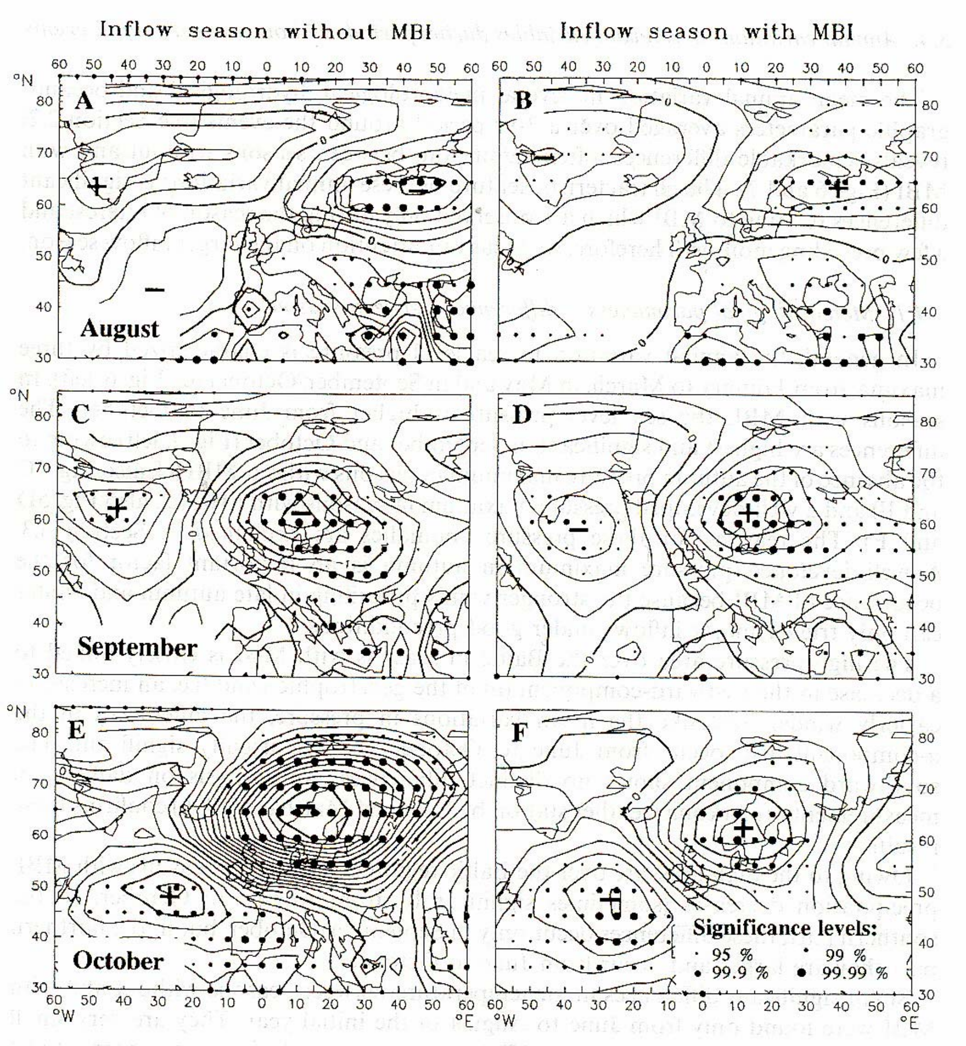

Fig. 8.1.
Mean anomaly in sea level pressure fields from August to October during both inflow seasons without (left) and with MBIs (right) (contour interval: 0.2 hPa) (from SCHINKE and MATTHÄUS 1998).

Abb. 8.1.
Mittlere Anomalien der Luftdruckfelder in Meeresspiegelhöhe von August bis Oktober in Einstromjahren ohne Salzwassereinbrüche (links) und in Einstromjahren mit Salzwassereinbrüchen (rechts) (Isobarenabstand: 0,2 hPa) (aus SCHINKE und MATTHÄUS 1998).

The inter-annual alternation between high and low salinity periods in the north-western European shelf seas (DICKSON 1971) are essentially identical to those observed in the deeper layers of the Kattegat (DICKSON 1973) and the Belt Sea (BÖRNGEN 1978, 1983). WYRTKI (1954b) – for the first time – called attention to the high salinity in the Kattegat deep water which is possibly a significant factor accounting for the occurrence of MBIs. DICKSON (1973) thinks that MBIs tend to occur at the time of salinification and high salinity conditions in the Kattegat deep water are

> "…thought to be favourable, if not essential, to the generation of major Baltic inflows" (DICKSON 1973, p. 96).

The results obtained by WYRTKI (1954b) and DICKSON (1971, 1973) led to the conclusion that the positive salinity anomaly in the Kattegat deep water must be an important oceanographic precondition for the occurrence of strong Baltic inflows (cf. FRANCKE and NEHRING 1971, BÖRNGEN 1978, 1983, FRANCKE and HUPFER 1980, BÖRNGEN et al. 1990).

The basis for this conclusion was the relatively small number of MBIs which had distinct effects on, primarily, the salinity, oxygen and nutrient conditions in the deep water of the central Baltic Sea (FONSELIUS 1981, 1985, NEHRING and FRANCKE 1981, FONSELIUS et al. 1984). WOLF (1972) and FRANCK et al. (1987) have shown that many more MBIs can be identified during the 20th century than have been detected by distinct effects in the Baltic deep basins (cf. also chapter 6), partly due to the lack of sufficiently long time series for the open Baltic deep water and partly because the effects of MBIs depend not only on the volume and salinity of the penetrated water but also of the density stratification existing at that time in the deep basins along the path of the inflowing saline water.

Based on a total of 43 MBIs in the post-war period between 1945 and 1976 identified at the Darss Sill MATTHÄUS and FRANCK (1989) studied the salinity conditions at four light vessels in the Kattegat deep water for the 30-day periods preceding the MBIs. They concluded that positive salinity anomalies in the Kattegat deep water are not a necessary precondition for MBIs. The anomalies ranged between –5 and +3 PSU in the central Kattegat and between –5 and +5.5 PSU in the southern Kattegat. Even strong inflows (Q_{96} > 20) occurred after both positive and negative anomalies.

This was supported by investigations carried out by LASS and SCHWABE (1990). They found that the monthly means in bottom salinity of the Skagerrak and Kattegat had no significant positive anomalies during four months before the strong MBI 1975/1976 started. They stated:

> "This contradicts the assumptions of Dickson (1973) and Börngen (1978) that a positive salinity anomaly in the Kattegat is a necessary precondition for a major salt water inflow but agrees with the results of the statistical analysis of salt water inflow events of Franck and Matthäus (1988)" (LASS and SCHWABE 1990, p. 118/119). "…there is always water in the bottom layer of the Kattegat of sufficient salinity for a major inflow into the Baltic" (LASS and SCHWABE 1990, p. 117).

The Bornholm Basin is the first Baltic deep basin downstream from the entrance sills. The filling stage of this basin with saline water is an essential precondition for the effectiveness of salt water inflows in the central Baltic basins downstream of the Bornholm Basin. Already KRÜMMEL (1895), FONSELIUS (1962) and GRASSHOFF (1975) pointed to that fact.

KRÜMMEL (1895) wrote on the propagation of the inflowing water:

> „Das Vordringen dieses Tiefenwassers ins Innere der Ostsee wird...wesentlich reguliert durch die Schwellen- oder Zugangstiefen, welche die einzelnen Trogmulden voneinander trennen." Die „...Bornholmer Mulde...ist...im Osten durch eine solche von ca. 60 m...begrenzt. Es kann...in diese Bornholmer Mulde Wasser von solchem Salzgehalt eindringen, wie er auf die Darßer Schwelle kommt. Das in dieser Mulde enthaltene Tiefenwasser bleibt dann darin..." (KRÜMMEL 1895, p. 86).

Later FONSELIUS (1962) informed on the importance of the Bornholm Basin:

> „The Bornholm Basin is surrounded by shallow banks and the only possibility for the heavy bottom water to continue into the rest of the Baltic is to flow over the 60 m sill to the Stolpe Channel…The high sill naturally prevents the heaviest water from continuing down into the rest of the Baltic…" (FONSELIUS 1962, p. 7).

KLAUS GRASSHOFF (1932 - 1981) decribed the buffering properties of the Bornholm Basin for three different models of salt water inflows GRASSHOFF (1975):

- Regular, most frequent inflows just below the permanent halocline interleaving on the level of neutral buoyancy.
  "Most of the inflowing water progresses further into the Baltic.…However, the water has a density which is usually insufficiently great for it to displace the old bottom water in the basins of the Baltic proper".

- Occasional inflows of higher saline water, penetrates to the bottom of the Bornholm Basin.
  "In most instances the rate of inflow is just great enough to replace the bottom water…, but is insufficient to fill the basin up the height of the sill".

- Episodic inflows of large amounts of highly saline water. The water is able
  "…first to replace the deep water in the Bornholm basin, to pass over the Slupsk Furrow and then to penetrate across the eastern sill of the furrow…down to the Gdansk Deep, or more gradually down into the Gotland Deep" (GRASSHOFF 1975, p. 478/479).

Realizing the topography of the Baltic Sea along the main transport route of the inflowing saline water (cf. Fig. 1A), the thermohaline conditions in the Bornholm Basin are also of considerable importance for the evolution of stagnation in the central Baltic deep water. In general, there is a frequent inflow of lower amounts of highly saline water, which penetrates across the sills into the Arkona Basin during each baroclinic or weak barotropic inflow event. This water is trapped in the Bornholm Basin renewing the ambient deep water to a certain extent and causes annual variations in the deep water (MATTHÄUS 1977, 1978, FRANCK 1985). The Bornholm Basin has a maximum depth of more than 90 m, but is separated from the downstream basins by the Stolpe Sill (sill depth: 60 m).

The filling stage of the Bornholm Basin below the permanent halocline with saline water is a measure for the estimation of the impact of weak inflows on the central Baltic deep water. During periods of low inflow activity, e.g. at the late 1980s (MATTHÄUS 1995), salinity and thus density of the Bornholm Basin deep water decreases. Depending on the inflowing volume of saline water and its density, inflows below the MBI magnitude - but even MBIs - fill up only that basin and the saline water does not pass to a greater extent the Stolpe Sill downstream through the Stolpe Channel into the Gotland Basin. An example characteristic for such situation was the very strong MBI in January 1993 which had only relatively weak impact in the central Baltic deep water (cf. Fig. 5.4 and MATTHÄUS et al. 1994, NEHRING et al. 1995).

When the buffering capacity of the Bornholm Basin is exhausted, weak inflows of saline and oxygen-rich water crossing the entrance sills into the Baltic can pass that basin in depths of 50 - 60 m, propagate downstream relatively quickly and cause significant effects in the central Baltic deep water. Such situation was observed after the MBI in January 1993 when the saline and oxygen-rich water of the weak inflows in December 1993 and March 1994 which did not obtain the magnitude of MBIs propagated relatively undisturbed and without significant mixing along its transport route into the eastern Gotland Basin (Fig. 8.2).

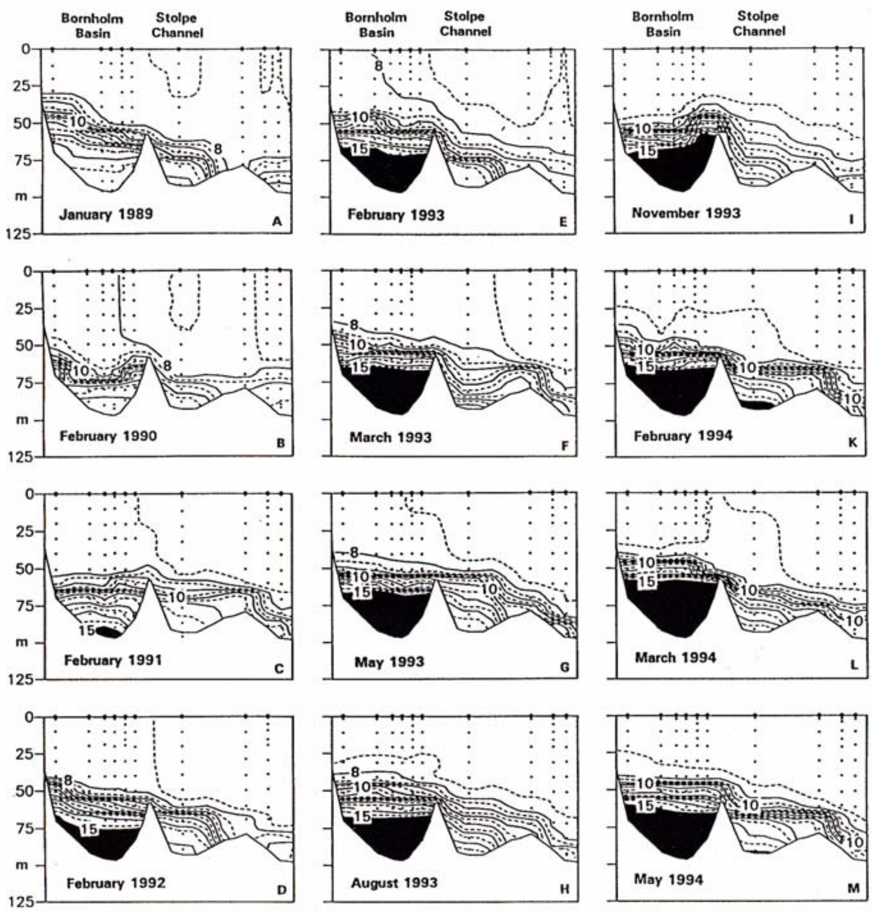

Fig. 8.2.
Variations of haline stratification in the Bornholm Basin and Stolpe Channel between 1989 and 1994, an example for the buffer capacity of the Bornholm Basin (black areas: salinity ≥15 PSU) (from MATTHÄUS et al.1994)

Abb. 8.2.
Veränderungen der halinen Schichtungsverhältnisse im Bornholmbecken und der Stolper Rinne zwischen 1989 und 1994, ein Beispiel für die Pufferkapatität des Bornholmbeckens (schwarz: Salzgehalte ≥15 PSU) (aus MATTHÄUS et al. 1994)

Similar effects were also observed in spring of the years 1996, 1997 and 1998 due to the regular filling of the Bornholm Basin with saline water >15 PSU during autumn of the previous years. Weak inflows between late autumn and early spring propagated relatively quickly into the eastern Gotland Basin renewing the deep water during the first half of the respective years (MATTHÄUS et al. 2001).

A warm water inflow in summer 2002 (FEISTEL et al. 2003c, 2004a) and a short inflow in November 2002 preceded the major event in January 2003. They supported the effect of the MBI in the central basins and the inflow in November replaced the bottom water in the Bornholm Basin. The MBI was followed by weak inflows in March and in May 2003. Both post-inflows enhanced the MBI because the Bornholm Basin was already filled with saline water and favoured the rapid eastward propagation into the eastern Gotland Basin (FEISTEL et al. 2003b).

9. The importance of exceptionally warm water inflows

Inflows of warm water in late summer and autumn into the Arkona and Bornholm Basins are regular annual processes. That can be shown by means of the long-term annual cycles in temperature in the deep water of the Arkona, Bornholm and Gdańsk Basins (cf. MATTHÄUS 1977, FRANCK 1985). Fig. 9.1 represents the mean annual variation of salinity and temperature in the western Bornholm Basin (in the visinity of the Christansø Deep) combined with the mean intermediate temperature maxima in the central Arkona and Bornholm Basins. It shows that - on average - temperatures of >12.5 ºC can be expected in the Arkona Basin in September/October, of >9 ºC in the western Bornholm Basin in October/November and of >8 ºC in the central Bornholm Basin between November and January.

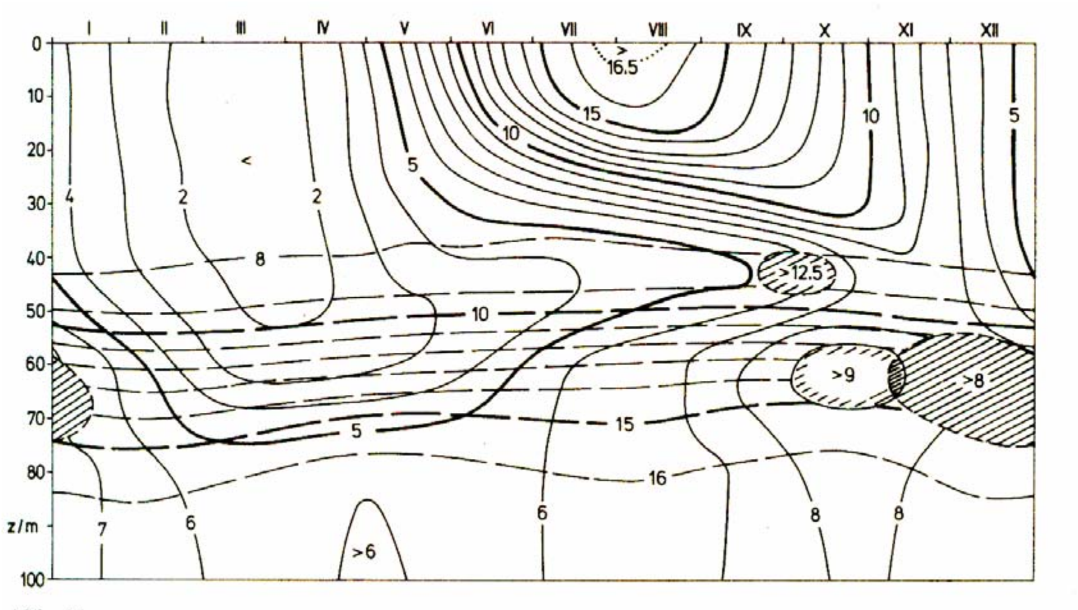

Fig. 9.1.
Mean annual variations in salinity (in PSU, hatched line) and temperature (in ºC, full line) in the western Bornholm Basin and mean intermediate temperature maxima (hatched area) in the central Arkona (>12.5 ºC) and Bornholm Basins (>8 ºC) (from FRANCK 1985).

Abb. 9.1.
Mittlere jahreszeitliche Schwankungen des Salzgehaltes (in PSU, gerissen) und der Temperatur (in ºC, ausgezogen) im westlichen Bornholmbecken sowie mittlere intermediäre Temperaturmaxima (schraffiert) im zentralen Arkona- (>12.5 ºC) und Bornholmbecken (>8 ºC) (aus FRANCK 1985).

In comparison with regular warm water inflows, the events transporting exceptionally warm water in summer and early autumn up to the central Baltic Sea are rare events. The causes of such inflows are of different nature. Two types have been observed:

- MBIs caused by heavy westerly gales which pass through both the Darss and Drogden Sills;
- long-lasting baroclinic inflows caused by calm weather conditions over central Europe which only pass through the Darss Sill.

In recent years, the attention of the Baltic oceanographers was called to baroclinic warm water inflows. Such processes can transport larger volumes of exceptionally warm water into the deeper layers of the central Baltic and they also seem to be important for the ventilation of intermediate layers in the eastern Gotland Basin deep water. Indeed, such inflows did not fulfil the criteria for MBIs (cf. chapter 6) but they can influence effectively the deep water of the Bornholm, Gdańsk and eastern Gotland Basins by higher salinity and temperature (cf. 100 m and 150 m level in Fig. 9.2). Nevertheless, barotropic *and* baroclinic warm water inflows transport less oxygen into the Baltic Sea and higher temperatures cause an increased rate of oxygen consumption in the deep water (KULLENBERG 1970) and such a faster formation of hydrogen sulphide. However, the summer inflows in 2002 and 2003 improved the oxygen conditions in the Bornholm and the eastern Gotland Basins due to entrainment of ambient water of higher oxygen on the way (FEISTEL et al. 2004a, MOHRHOLZ et al. 2006).

The special attention was called by the persistent baroclinic inflow of unusually warm water over a period of about eight weeks in August/September 2002 (FEISTEL et al. 2003c, 2004a, MOHRHOLZ et al. 2006) which resulted in 2003 in the highest temperatures measured in intermediate layers of the central Baltic Sea (Fig. 9.2, 100 m level).

Between the end of June and mid-September 2002, moderate easterly winds prevailed over the western Baltic. A near-bottom current with a mean layer thickness of about 5 m and salinities >14 PSU (maximum bottom values: up to 20 ºC and 20 PSU, respectively) transported warm, saline water across the Darss Sill into the Arkona Basin (NAUSCH et al. 2003). This inflow also caused a ventilation of the deep water in the Gdańsk Deep and a reduction of the H_2S concentrations in the Gotland Deep.

In summer 2003, another baroclinic warm water inflow occurred (FEISTEL et al. 2004b, PIECHURA and BESZCZYŃSKA-MÖLLER 2004) connected with an increase in temperature and salinity of the central Baltic deep water in 2004. In the Gotland Basin, the density of the inflowing water was capable of lifting up the ambient deep water. Temperatures of 7.2 ºC and salinities of 13.2 PSU were measured in the near-bottom layer of the Gotland Deep in February 2004 (NAUSCH et al. 2005).

Deep water temperatures as high as in 2003 and 2004 have also been observed earlier (cf. Fig. 9.2). However, processes of such extent, strength and frequency have never been described before. Inflows of unusually warm water have been observed in 1959 (FEISTEL et al. 2004a), in 1976 (FONSELIUS 1977) and in 1997 (MATTHÄUS et al. 1998, HAGEN and FEISTEL 2001), and they resulted in distinct effects in the central Baltic Sea (MATTHÄUS et al. 1999, FEISTEL et al. 2004a). Another weak warm water inflow occurred in autumn 2001 traced by FEISTEL et al. (2003a) and documented by the temperature recordings at the long-term mooring near the Gotland Deep (FEISTEL et al. 2006).

Whereas the event in 1959 could be comparable with the summer inflow in 2003 the increase in deep water temperatures in 1977 and 1998 was mainly caused by barotropic inflows during moderate MBIs in November/December 1976 (Q_{96} = 13; cf. Fig. 6.2) and in September 1997 (Q_{96} = 11.2; cf. Fig. 6.2). Fig. 9.2 shows long-term variations of temperature in intermediate levels (mainly caused by baroclinic warm water inflows) and in the near-bottom layer of the Gotland Deep (mainly caused by MBIs).

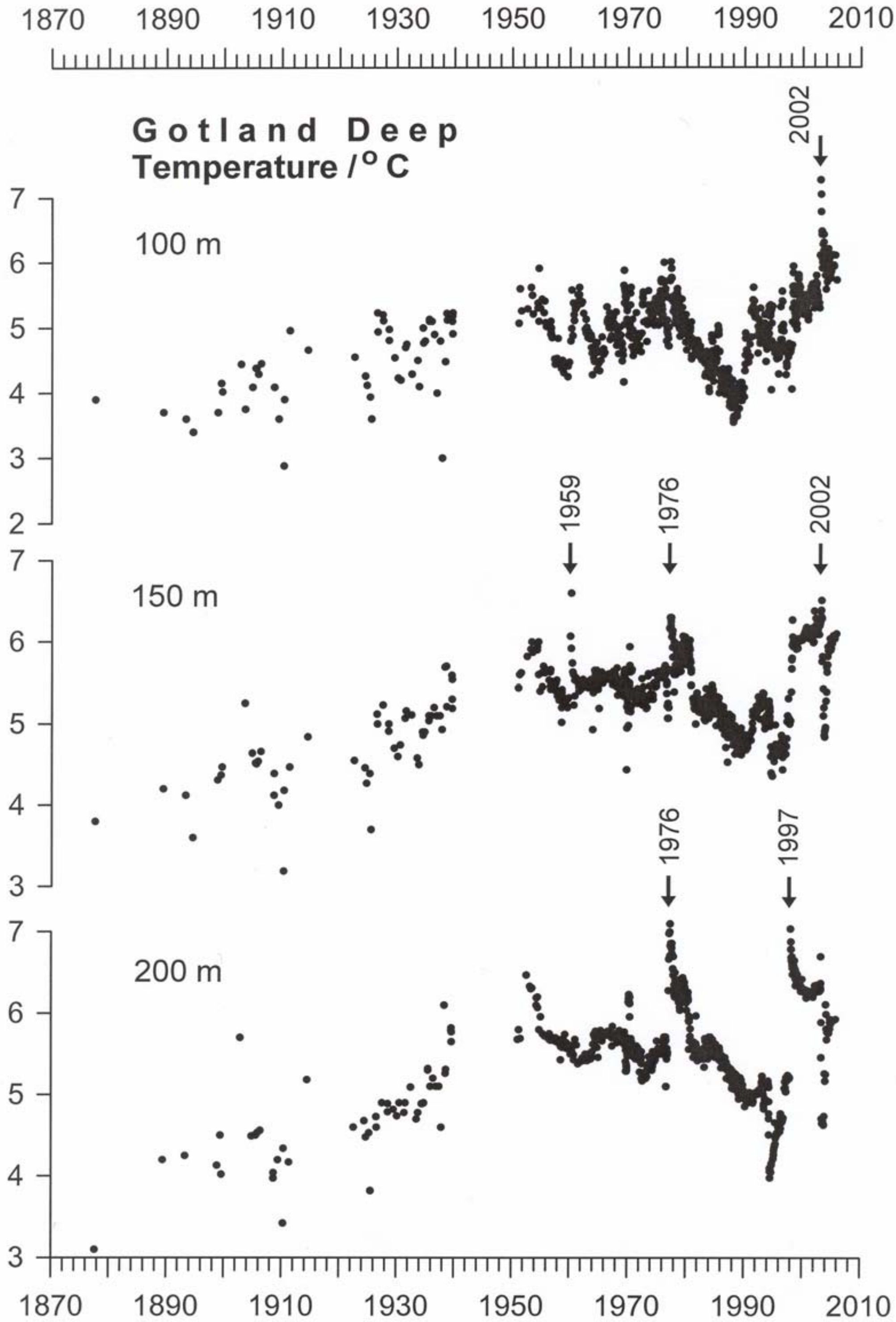

Fig. 9.2.
Long-term variations of temperature at three levels of the deep water in the Gotland Deep. Signals of warm water inflows are indicated by arrows.

Abb. 9.2.
Langzeitvariationen der Temperatur in drei Horizonten des Tiefenwassers im Gotlandtief. Die Signale der Warmwasser Einströme sind durch Pfeile markiert.

In December 1975/January 1976, a strong MBI (Q_{96} = 25.6; cf. No. 15 in Table 6.2) occurred and led to the renewal of the deep water in the central Baltic basins (cf. chapter 5.2). In late autumn 1976, an increased inflow activity was observed at the Darss Sill (NEHRING and FRANCKE 1978) which culminated in November/December 1976 in a moderate MBI (Q_{96} = 13). Four periods of barotropic inflows in August, September, October and November were recorded by a permanent buoy station at the Darss Sill. During these inflow periods of about 8 – 10 days each, saline and warm water was transported into the central Baltic Sea. The buffering capacity of the Bornholm Basin was exhausted by the strong MBI at the turn of 1975 to 1976. Therefore, the warm water penetrated between August and October combined with the saline and oxygen-rich water, transported during the moderate MBI in late 1976, passed the Bornholm Basin in intermediate depths and propagated quickly and relatively undisturbed into the eastern Gotland Basin (NEHRING and FRANCKE 1980).

The inflow was traced by r/v "Professor Albrecht Penck" and the Swedish r/v "Argos". FONSELIUS (1977) described the process and effect of the inflow in the central Baltic deep water in detail. The warm water body of temperatures >10 ºC passed the Stolpe Sill in November 1976 and propagated into the eastern Gotland Basin (Fig. 9.3). The warm water had reached the Gotland Deep already in January 1977, caused an increase in temperature of the near-bottom layer up to 7.4 ºC, the highest temperatures recorded so far (cf. Fig. 9.2, 200 m level). The salinity increased to >13 PSU in January 1977. During 1977, the inflow led to a distinct increase in salinity and oxygen concentration and - since ten years – the deep water of the whole Baltic was free of hydrogen sulphide in May (NEHRING and FRANCKE 1980).

Special attention was paid to the warm water inflow in autumn 1997. After a renewed check of all available data this inflow must be regarded as a moderate MBI (cf. chapter 5).

The summer of 1997 was one of the warmest since 1890. Similar warm were only the summers of 2002 and 2003. The major inflow occurred between 15 and 21 September at the Darss Sill. Two storms in September and early October transported larger volumes of exceptionally warm and saline water across both sills into the Baltic. This led to temperature anomalies of 3 – 4 K in the central Bornholm Basin deep water. At the end of October 1997, the whole Bornholm Basin deeper than 60 m was filled with water having salinities >15 PSU, and warm (9 – 11 ^{o}C), saline (14 – 15 PSU) and oxygen-rich water (up to 2.5 ml/l) crossed the Stolpe Sill into the central Baltic Sea. By the beginning of November, this water body had reached the southern slope of the eastern Gotland Basin (MATTHÄUS et al. 1998). The inflow process into the Gotland Basin was settled in May 1998. Temperatures increased from about 5 ^{o}C to about 6 ^{o}C between 140 and 170 m depth (HAGEN and FEISTEL 2001, cf. also Fig. 5.6), and reached more than 7 ^{o}C in the near-bottom layer of the Gotland Deep (MATTHÄUS et al. 1999).

Both MEIER et al. (2004) and LEHMANN et al. (2004) carried out first model simulations of the baroclinic summer inflows in 2002. The model developed by MEIER et al. (2004) simulated the evolution of the summer inflows in August/September and November 2002 and their effects for the deep water ventilation in the Arkona, Bornholm and Gotland Deeps. Also the fully coupled regional model developed by LEHMANN et al. (2004) successfully reproduced the inflow of the exceptional warm water in 2002.

Baroclinic warm water inflows in summer and early autumn seem to be an indication for a new quality in long-term behaviour of the Baltic Sea.

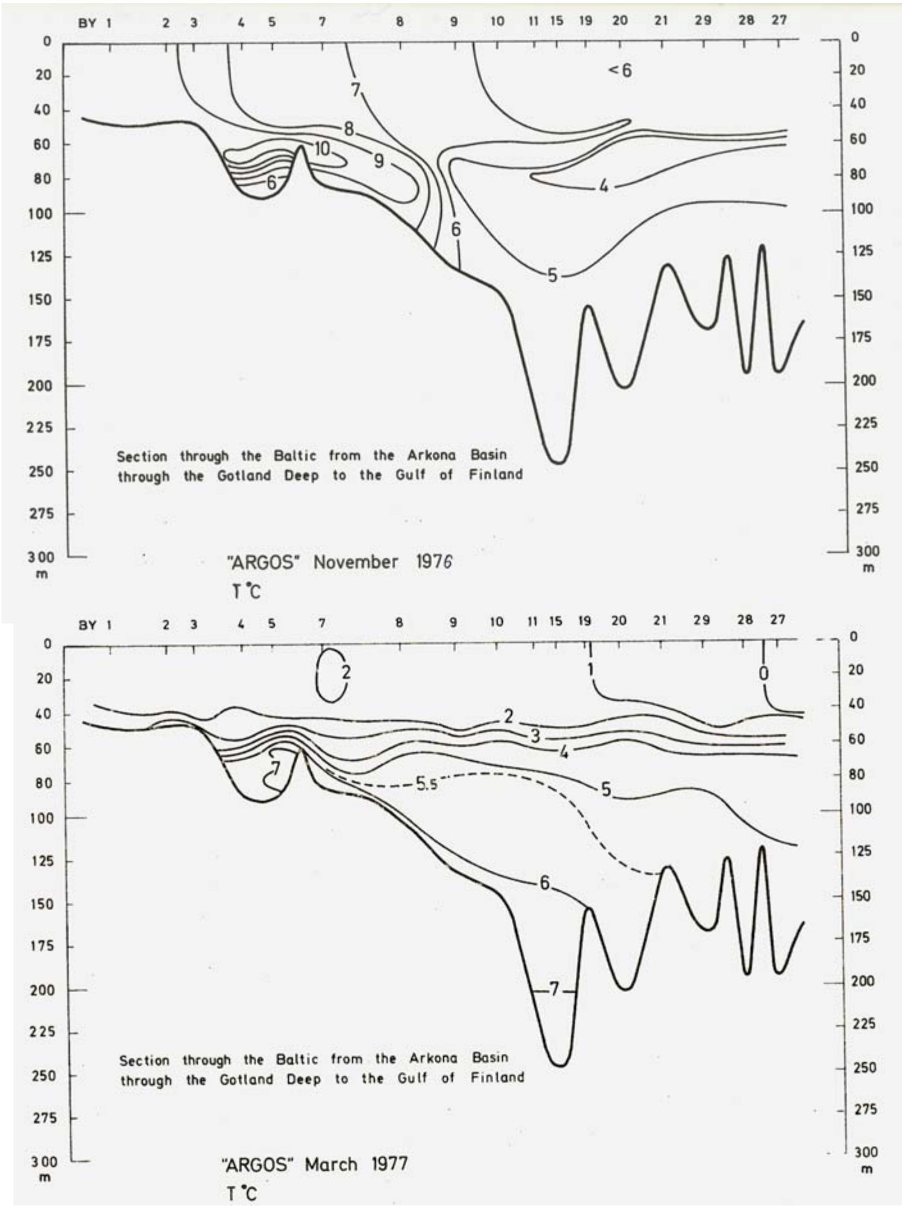

Fig. 9.3.
Inflow of unusually warm water into the central Baltic Sea, observed by the Swedish research vessel "Argos" in November 1976 and March 1977 (from FONSELIUS 1977).

Abb. 9.3.
Einstrom von ungewöhnlich warmem Wasser in die zentrale Ostsee, beobachtet durch das schwedische Forschungsschiff "Argos" im November 1976 und March 1977 (aus FONSELIUS 1977).

10. Simulation of MBIs by numerical models

Since the 1970s, modelling efforts of wind-driven circulation (e.g. SIMONS 1978, KIELMANN 1981), of water exchange between the North Sea and the Baltic (e.g. STIGEBRANDT 1983, SEIFERT and FENNEL 1994, SCHMIDT et al. 1998) and of thermohaline circulation in the Baltic basins (e.g. STIGEBRANDT 1987, GIDHAGEN and HÅKANSSON 1992) have been made. The results of statistical analysis of MBIs (cf. chapter 6) and investigations on their causes (cf. chapter 7) suggested to intensify the study of MBIs by using numerical models.

The history of simulation of MBIs by means of numerical modelling started in 1993. The exceptional MBI in January 1993 (cf. section 5.3) was the reason for first attempts to model inflows of highly saline water into the Baltic Sea. During the ICES Statutory Meeting in 1993, a complete session was organized in order to discuss the very strong January 1993 inflow. ECKHARD KLEINE (1993) presented numerical simulations of the 1993 event. ANDREAS LEHMANN (1993) informed on activities in order to simulate MBIs and showed results using the very strong inflow in 1951 as an example. In 1994, LEHMANN (1994a, b) improved his model and presented new results on the simulation of MBIs both during the ICES Statutory Meeting and the Conference of Baltic Oceanographers.

For the first time, a MBI has been simulated by an operational model of the North Sea and the Baltic (KLEINE 1993). The model was running in the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH) in Hamburg and continuously forecasted sea levels and currents. In 1992, a baroclinic version was initialized and the model simulated the evolution of sea level, current, salinity and temperature. The atmospheric dynamics as simulated by the German Weather Service for January 1993 triggered the MBI in the numerical model and demonstrated the main features of the major inflow in January 1993. However, it insufficiently described details of the evolution of temperature and salinity (HUBER et al. 1994). The weakness of the model was the poor vertical resolution and the uncertainties in modelling of horizontal and vertical transfer of momentum, temperature and salt.

LEHMANN (1994a, b) used a three-dimensional eddy-resolving baroclinic model of the Baltic Sea (LEHMANN 1992) in order to simulate the January 1993 MBI and its impact on the Baltic. The model had a horizontal resolution of 5 km and 21 levels. It was forced by realistic wind fields computed from atmospheric surface pressure maps. The simulation resulted in a realistic salinity distribution, but the depth of the mixed layer was underestimated by the model and, as a consequence, the vertical gradient of the salinity across the halocline was too weak (LEHMANN 1995).

The MBI in January 1993 formed the basis for increased modelling activities (MEIER 1996, GUSTAFSSON 2000, ANDREJEV et al. 2002, MEIER et al. 2003, MEIER and KAUKER 2003, LEHMANN et al. 2004).

MEIER (1996) developed a three dimensional baroclinic model of the western Baltic in order to calculate the water and salt exchange between the North Sea and the Baltic. He selected the period between September 1992 and September 1993 as a test period which included the very strong MBI in January 1993. The volume and salt transports during the MBI simulated by the model showed a good agreement with observations. The results also showed the importance of the Drogden Sill for MBIs.

GUSTAFSSON (2000) developed a hydrodynamic model with the aim to make time-dependent calculations of the circulation in the Baltic entrance area. The fluxes of water and salt across the Darss Sill were computed from the model for both the precursory and inflow periods. During two periods (1950 – 1953, 1961 – 1993), GUSTAFSSON simulated five of the strongest MBIs among them the 1993 event. The model is able to reproduce the characteristics of MBIs fairly well, however, the magnitude of the flow of water and salt appears lower than other estimates.

ANDREJEV et al. (2002) used a three-dimensional, baroclinic hydrodynamic model with a horizontal resolution of 2 nm and 40 vertical levels in order to simulate the dynamics of the Janaury 1993 event. The model reproduced rather well the inflow-outflow system at the entrance area including the observed imbalance between the saline water flowing into the Arkona Basin from the Darss Sill and that flowing out into the Bornholm Basin (cf. MATTHÄUS and LASS 1995).

In order to study the processes responsible for the generation of mesoscale cyclonic eddies in the eastern Gotland Basin following inflow events, ZHURBAS et al. (2003) carried out numerical experiments using the Princeton Ocean circulation Model POM (BLUMBERG and MELLOR 1980, 1983). Model runs showed that the bottom intrusions of saline water splitted into two branches when entering the eastern Gotland Basin from the Stolpe Channel: one branch went northeast towards the Gotland Deep, the other moved southeast towards the Gdańsk Deep. An intensive cyclonic eddy carrying the saline water is generated just east of the Stolpe Channel with the inflow pulse. A series of smaller cyclonic eddies are formed in the permanent halocline along the pathway of the saline water to the Gotland Deep.

MEIER, DÖSCHER and FAXÉN (2003) used the three-dimensional coupled ice-ocean model of the Rosby Center in Norrköping (RCO model) in order to hindcast the period from May 1992 to June 1993 (including the major inflow in January 1993) and the period 1980 –1993 (within the 16-year stagnation period between 1976 and 1992). The RCO model had a horizontal resolution of 2 nm and 41 vertical levels with layer thickness between 3 and 12 m. The agreement between model results and observations was regarded as good. Results have shown that in short simulations the January 1993 MBI was simulated rather well, but the salt transport between the Arkona Basin and the Bornholm Basin was underestimated. The sensitivity experiments for the January 1993 event suggested a significant impact of river runoff and the sea level in the Kattegat on MBIs.

Hindcast simulations of the Baltic Sea for the period 1902 – 1998 using the RCO model have shown that increased runoff and precipitation reduce the intensity of MBIs but can not explain the stagnation periods in the central Baltic deep water during the 1920/1930s and the 1980/1990s completely (MEIER and KAUKER 2003). During the stagnation periods, anomalous strong westerly winds caused increased sea levels and reduced salt transports into the Baltic Sea. Additionally, increased runoff and precipitation changed the baroclinic pressure gradient on a slower time scale that the salt transports were further reduced. The model results agreed well with the analysis of observed long time series carried out by SCHINKE and MATTHÄUS (1998).

MEIER et al. (2004) studied the MBI in January 2003 in combination with the smaller inflows in summer/autumn 2002 (FEISTEL et al. 2003b, c) using the RCO model. Based on a long hindcast simulation from May 1980 to December 2003 model results of both the MBI in January 2003 and the consequences of summer inflows in August/September and November 2002 (cf. chapter 9) are analyzed. The simulation of the MBI including the volumes of penetrated highly saline water was in good agreement with observations. In principle, the ventilation of the deep water in the Bornholm and eastern Gotland Basins was simulated realistically by the RCO model.

LEHMANN et al. (2004) developed a coupled model system for the Baltic Sea region (BALTIMOS) by linking existing model components for the atmosphere, for the ocean including sea ice, for hydrology and for lakes. The simulation period from February 2002 to October 2003 included the exceptional warm water inflow in summer and autumn 2002 and the MBI in January 2003. The model results were in close agreement with the observations by FEISTEL et al. (2003b, c). The fully coupled regional model successfully reproduced both the overall mass exchange during the simulation period and the inflow of water during the different events and its distribution in the Bornholm Basin.

An interesting model study was performed by GUSTAFSSON and ANDERSSON (2001). They simulated the occurrence and strength of MBIs by means of a semi-empirical model using the north-south air pressure gradient across the North Sea as the only forcing. A total of 118 inflow events were identified between 1902 and 1998 on condition that at least 50 km^3 of water with salinities >17 PSU must pass the sills during an event. FISCHER and MATTHÄUS (1996) identified a total of 88 MBIs for that period. Ten of the 20 highest ranked MBIs in Table 6.2 were among the 13 strongest events identified by the model calculations of GUSTAFSSON and ANDERSSON.

The better numerical simulations reproduce mechanism, causes and effects of major inflows of highly saline water into the Baltic Sea the sooner it will be possible to investigate MBIs by means of models in more detail as it can be achieved by observations. The recent developed coupled models demonstrate that modelling is a valuable tool for simulation of the water exchange in order to obtain a better understanding of the processes behind MBIs.

Summary

Inflows of highly saline water into the Baltic Sea – termed major Baltic inflows (MBIs) – are one of the basic phenomena of the Baltic Sea. MBIs have episodic character, and are the essential mechanism by which the central Baltic deep water is renewed. A short introduction on MBIs and their importance for the environmental conditions of the Baltic deep water is given in chapter 1.

Chapter 2 starts with the oldest information on properties of the Baltic Sea water dating back to the late 18th century (WILCKE 1771, BLADH 1776). As early as at the beginning of the 19th century, publications on salinity and the causes for the salt in the Baltic Sea are known (CATTEAU-CALLEVILLE 1815, MARCET 1819, von SIVERS 1820). MEYER (1871) was one of the first who investigated the physical conditions in the western Baltic Sea. KRÜMMEL (1894, 1895) and KNUDSEN (1899, 1900a, b) have investigated the problem of renewal of the Baltic deep water as early as the end of the 19th century.

At the end of the 19th century, it was known that inflows of saline water into the Baltic Sea cause the renewal of the deep water in the central basins (MEYER 1871, KARSTEN 1874, PETTERSSON 1893). Inflows take place intermittently and are governed by the strength of westerly winds. Salinity and temperature were used as indicators for the renewal process but the concentration of dissolved oxygen was also used (PETTERSSON 1894). For the first time, a salinity of 17 PSU in the Kadet Channel is mentioned to be not sufficient for a renewal of the near-bottom layers in the central basins (KNUDSEN 1900a). The importance of the Sound for the inflow was underestimated (JACOBSEN 1873, KRÜMMEL 1894, KNUDSEN 1900a). It is already supposed that the transport of salt into the Baltic could be influenced by the Baltic sea level (MEYER 1871).

In the late 19th century, the investigations on board of the German steamer "Pommerania" in 1871 (MEYER et al. 1873), the Swedish expeditions in 1877 (EKMAN and PETTERSSON 1893) and the Russian observations on board of the corvette "Vitiaz" in 1886 and 1889 (MAKAROFF 1894) yielded essential knowledge on the mechanism of water exchange across the Belts and the Sound and the propagation of salt water within the Baltic Sea (cf. chapter 3).

In chapter 4, the importance for MBI research of the international observation programmes carried out during the early 20th century is explained. During the first half of the 20th century, Baltic oceanographers were occupied with the general investigation and description of both the exchange processes and the effects of salt water inflows in the Baltic Sea. More detailed knowledge on the stagnation and turnover processes in the central Baltic deep water existed (KALLE 1943). Comprehensive investigations of the water exchange between the North Sea and the Baltic and the weather situation during inflow and outflow were carried out (MANEGOLD 1936, KÄNDLER 1951, WYRTKI 1954a). There was the first detailed investigation of sea level variations and currents in the Danish Straits before and during MBIs (HELA 1944).

The interest in MBIs obtained a new impulse by the occurrence of the strongest event observed so far in 1951. WYRTKI (1954b) started detailed investigations of major Baltic inflows and studied the dynamic processes in the transition area during the MBI in November/December 1951. Between the 1960s and the 1990s, the cycle of water renewals has been well documented by the analysis of specific events (chapter 5). FONSELIUS (1962) started the detailed description of the effects of MBIs in the central Baltic deep water. In 1970, he began on systematic identification of MBIs by means of variations in oceanographic parameters in the eastern Gotland Basin deep water (FONSELIUS and RATTANASEN 1970). It provides information on detailed investigations of the strong and very strong MBIs in December 1975/January 1976 (FRANCKE et al. 1978, FRANCKE and

HUPFER 1980, LASS and SCHWABE 1990), in January 1993 (DAHLIN et al. 1993, HÅKANSSON et al. 1993, MATTHÄUS et al. 1993, JAKOBSEN 1995, LILJEBLADH and STIGEBRANDT 1996, PAKA 1996, ZHURBAS and PAKA 1997) and in January 2003 (FEISTEL et al. 2003b, PIECHURA and BESZCZYŃSKA-MÖLLER 2004).

In chapter 6, contributions on the statistical analysis of major Baltic inflows are described based on the time series of MBIs. During the 1970s, investigations started to focus on comparable measures for identification of MBIs (WOLF 1972, FRANCK et al. 1987) and on the analysis of long time series of the characteristic properties (temperature, salinity, oxygen content) of the water penetrating during MBIs (FRANCK et al. 1987, MATTHÄUS and FRANCK 1988, 1992). Investigations on the water volumes entering the Baltic before and during MBIs (MATTHÄUS and FRANCK 1990), on the Baltic sea level variations (FRANCK and MATTHÄUS 1992) and on the meteorological conditions (wind, atmospheric circulation) before and during MBIs were carried out (LASS and MATTHÄUS 1996, MATTHÄUS and SCHINKE 1994, SCHINKE and MATTHÄUS 1998). The importance of the Drogden Sill for MBIs had been investigated and the reasons for re-assessment of the intensity in the 1990s are explained (FISCHER and MATTHÄUS 1996).

Short historical reviews on investigations of the causes and on the preconditions for the occurrence of MBIs are given in chapters 7 and 8. In chapter 9, the contributions on barotropic and baroclinic warm water inflows in late summer and autumn and their importance for the central Baltic deep water are described.

The results of statistical analysis of MBIs and investigations of their causes suggested to intensify the study of MBIs by using numerical models. In chapter 10, a brief overview on the history of simulation of MBIs is compiled which started in 1993 (KLEINE 1993, LEHMANN 1994b). The recent developed coupled models (LEHMANN et al. 2004, MEIER et al. 2004) show a good agreement between the simulation of the MBI and the observations.

An extensive list of references contains most of the relevant historical papers up to the most recent publications on major inflows of highly saline water into the Baltic Sea.

Zusammenfassung

Größere Einströme von Salzwasser in die Ostsee – als Salzwassereinbrüche bezeichnet – sind eines der grundlegenden Phänomene der Ostsee. Sie haben episodischen Charakter und stellen einen wesentlichen Mechanismus dar, durch den das Tiefenwasser der zentralen Ostsee erneuert wird. Eine kurze Einführung über Salzwassereinbrüche und ihre Bedeutung für die Umweltbedingungen im Tiefenwasser der Ostsee wird in Kapitel 1 gegeben.

Kapitel 2 beginnt mit den ältesten Informationen über Eigenschaften des Ostseewassers, die auf das späte 18. Jahrhundert zurückgehen (WILCKE 1771, BLADH 1776). Schon zu Anfang des 19. Jahrhunderts sind Veröffentlichungen über den Salzgehalt und die Ursachen für das Salz in der Ostsee bekannt (CATTEAU-CALLEVILLE 1815, MARCET 1819, von SIVERS 1820). MEYER (1871) war einer der ersten, der die physikalischen Bedingungen in der westlichen Ostsee erforschte. Bereits Ende des 19. Jahrhunderts haben KRÜMMEL (1894, 1895) und KNUDSEN (1899, 1900a, b) das Problem der Erneuerung des Tiefenwassers der Ostsee untersucht.

Endes des 19. Jahrhunderts war bekannt, dass die Erneuerung des Tiefenwassers der zentralen Becken der Ostsee durch die Einströme von Salzwasser verursacht wird (MEYER 1871, KARSTEN

1874, PETTERSSON 1893). Einströme treten episodisch auf und werden durch die Stärke der westlichen Winde gesteuert. Salzgehalt und Temperatur dienten als Indikatoren für den Erneuerungsprozess, aber die Konzentration des gelösten Sauerstoffs wurde auch bereits genutzt (PETTERSSON 1894). Zum ersten Mal wird erwähnt, dass ein Salzgehalt von 17 PSU in der Kadetrinne nicht ausreichend ist, um eine Erneuerung der bodennahen Schichten in den zentralen Becken zu bewirken (KNUDSEN 1900a). Die Bedeutung des Sundes für den Einstrom wurde unterschätzt (JACOBSEN 1873, KRÜMMEL 1894, KNUDSEN 1900a). Es wurde bereits vermutet, dass der Transport von Salz in die Ostsee durch den Ostsee-Wasserstand beeinflusst werden könnte (MEYER 1871).

Die Untersuchungen auf dem deutschen Dampfer „Pommerania" im Jahre 1871 (MEYER et al. 1873), die schwedischen Expeditionen 1877 (EKMAN and PETTERSSON 1893) und die russischen Beobachtungen auf der Korvette „Vitias" 1886 und 1889 (MAKAROFF 1894) lieferten wesentliche Erkenntnisse über den Mechanismus des Wasseraustausches durch die Belte und den Sund und die Ausbreitung des Salzwassers in der Ostsee (s. Kapitel 3).

Die Bedeutung der internationalen Beobachtungsprogramme des frühen 20. Jahrhunderts für die Erforschung der Salzwassereinbrüche wird in Kapitel 4 erläutert. In der ersten Hälfte des 20. Jahrhunderts waren die Ostseeozeanographen mit der allgemeinen Untersuchung und Beschreibung sowohl der Austauschprozesse als auch der Auswirkungen von Salzwassereinbrüchen befasst. Es gab bereits genauere Kenntnisse über die Stagnations- und Umschichtungsprozesse im Tiefenwasser der zentralen Ostsee (KALLE 1943). Detaillierte Untersuchungen über den Wasseraustausch zwischen Nord- und Ostsee und die Wetterbedingungen bei Ein- und Ausstrom wurden durchgeführt (MANEGOLD 1936, KÄNDLER 1951, WYRTKI 1954a). Es gab die erste detaillierte Untersuchung der Wasserstandsschwankungen und Strömungen in den Dänischen Meeresstraßen vor und während Salzwassereinbrüchen (HELA 1944).

Durch den stärksten bisher beobachteten Salzwassereinbruch im Jahre 1951 erhielt das Interesse an Salzwassereinbrüchen einen neuen Impuls. WYRTKI (1954b) begann detaillierte Untersuchungen über Salzwassereinbrüche und studierte die dynamischen Prozesse im Übergangsgebiet während des Salzwassereinbruchs im November/Dezember 1951. In den 60er bis 90er Jahres des vorigen Jahrhunderts wurden die Wassererneuerungen gut dokumentiert durch die Analyse spezieller Ereignisse (Kapitel 5). FONSELIUS (1962) begann mit der detaillierten Beschreibung der Auswirkungen von Salzwassereinbrüchen im Tiefenwasser der zentralen Ostsee. Im Jahre 1970 startete er die systematische Identifizierung von Salzwassereinbrüchen an Hand der Variationen ozeanographischer Parameter im Tiefenwasser des östlichen Gotlandbeckens (FONSELIUS and RATTANASEN 1970). Über die detaillierte Erforschung der starken und sehr starken Salzwassereinbrüche im Dezember 1975/Januar 1976 (FRANCKE et al. 1978, FRANCKE and HUPFER 1980, LASS and SCHWABE 1990), im Januar 1993 (DAHLIN et al. 1993, HÅKANSSON et al. 1993, MATTHÄUS et al. 1993, JAKOBSEN 1995, LILJEBLADH and STIGEBRANDT 1996, PAKA 1996, ZHURBAS and PAKA 1997) und im Januar 2003 (FEISTEL et al. 2003b, PIECHURA and BESZCZYŃSKA-MÖLLER 2004) wird berichtet.

Im Kapitel 6 werden die statistischen Untersuchungen von Salzwassereinbrüchen auf der Basis von Zeitreihen zusammengefasst. In der 1970er Jahren begannen sich die Forschungen auf vergleichbare Maße zur Identifizierung von Salzwassereinbrüchen (WOLF 1972, FRANCK et al. 1987) und auf die Analyse von Langzeitreihen charakteristischer Eigenschaften (Temperatur, Salzgehalt, Sauerstoffgehalt) des bei Salzwassereinbrüchen eindringenden Wassers zu konzentrieren (FRANCK et al. 1987, MATTHÄUS and FRANCK 1988, 1992). Untersuchungen über die vor und während der Salzwassereinbrüche einströmenden Wasservolumina (MATTHÄUS and

FRANCK 1990), über die Schwankungen des Wasserstandes der Ostsee (FRANCK and MATTHÄUS 1992) und über die meteorologischen Bedingungen (Wind, atmosphärische Zirkulation) vor und während der Salzwassereinbrüche wurden durchgeführt (LASS and MATTHÄUS 1996, MATTHÄUS and SCHINKE 1994, SCHINKE and MATTHÄUS 1998). Die Bedeutung der Drodgen-Schwelle für Salzwassereinbrüche wurde untersucht und die Gründe für eine Neubewertung der Intensität in den 1990er Jahren erläutert (FISCHER and MATTHÄUS 1996).

Ein kurzer historischer Überblick über die Erforschung der Ursachen und der Vorbedingungen für das Auftreten von Salzwassereinbrüchen wird in den Kapiteln 7 und 8 gegeben. Im Kapitel 9 werden die Arbeiten über barotrope und barokline Einströme warmen Wassers im Spätsommer und Herbst sowie ihre Bedeutung für das Tiefenwasser beschrieben.

Die Ergebnisse der statistischen Analyse der Salzwassereinbrüche und die Erforschung ihrer Ursachen legten nahe, die Untersuchung von Salzwassereinbrüchen mit Hilfe numerischer Modelle zu intensivieren. In Kapitel 10 ist ein kurzer Überblick über die Geschichte der Simulation von Salzwassereinbrüchen zusammengestellt, die im Jahre 1993 begann (KLEINE 1993, LEHMANN 1994b). Die jüngst entwickelten gekoppelten Modelle (LEHMANN et al. 2004, MEIER et al. 2004) zeigen eine gute Übereinstimmung zwischen Simulation und den Beobachtungen.

Ein umfangreiches Literaturverzeichnis enthält die meisten der relevanten historischen Arbeiten bis zu den neuesten Veröffentlichungen über Salzwassereinbrüche.

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