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Abstract

Sea ice conditions in the Baltic Sea have been systematically monitored for more than 100 years. All sea ice-related parameters display large interannual variability, but a change towards milder ice winters has been observed over the past 100 years: in particular, the annual maximum ice extent has decreased and the length of the ice season has become shorter. There is no correlation between consecutive ice seasons because the thermal memory of the Baltic Sea is only 2–3 months. Interannual variability in sea ice conditions is principally driven by the large-scale atmospheric circulation, described by the North Atlantic Oscillation. In addition to a tendency towards milder winters, the occurrence of severe ice winters has also decreased considerably over the past 25 years.

Keywords

Sea ice • Extent • Duration • Thickness • Climate variations and change • Baltic Sea

8.1 Introduction

The importance of understanding the variability and changes in sea ice has been recognised for centuries. The first written accounts of ice conditions in the Baltic Sea were documented in harbour logbooks of the Fourteenth century (Tarand and Nordli 2001; Schmelzer and Holfort 2011). A regular observational network was established in the nineteenth century among the Baltic Sea countries, mainly to provide guidance

for shipping (Jevrejeva et al. 2004), but later for scientific analyses of ice conditions (Speerscheider 1927; Jurva 1937; Palosuo 1953). In the first Baltic Sea assessment (BACC Author Team 2008), Schmelzer et al. (2008) and Vihma and Haapala (2009) gave extensive summaries of the existing literature. This chapter updates those reviews but does not repeat the extensive discussions already published.

The state of sea ice is determined by its extent, thickness and drift. Among these variables, ice extent is the most reliable measured quantity. In the past, ice extent was determined by visual observations from the coast, ships and aircraft, but since the start of the satellite era in the 1970s, accurate daily measurements are possible. In the Baltic Sea, regular ice thickness measurements are limited to the land-fast ice sites. These measurements, conducted by drilling, although accurate represent variations in ice thickness for coastal areas only. Sea ice drift can be determined by position logging buoys (Leppäranta et al. 2001) or by detecting sea ice displacement using pairs of satellite images (Leppäranta et al. 1998; Karvonen 2012), but so far, no studies have been conducted focusing on long-term variability and

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changes in sea ice drift. Apart from these basic physical variables, the length of the ice season and dates of freezing and break-up of the ice cover have also been widely used as climatological indicators of ice season severity.

The Baltic Sea ice season usually lasts for six to eight months. Typically, coastal shallow areas in the Bothnian Bay become ice-covered in October–November. During the next phase, the ice cover advances towards the central parts of the Bothnian Sea, and coastal areas of the other Baltic Sea sub-basins also become ice-covered. On average, the ice-covered area is greatest in March, when the maximum ice extent in the Baltic Sea (MIB) is about 165,000 km², or 40 % of the total area of the Baltic Sea. The limit of the ice is typically located in the northern Baltic Proper, which means the Gulf of Bothnia, Gulf of Finland and Gulf of Riga are all completely ice-covered. In extremely severe winters, the entire Baltic Sea has been ice-covered (420,000 km²). During the mildest winters, sea ice is formed only in the Bothnian Bay and the eastern Gulf of Finland. The minimum MIB to date is 49,000 km². The length of the ice season is 130–200 days in the Bothnian Bay, 80–100 days in the Gulf of Finland and 0–60 days in the southern Baltic Sea.

Near the shore, sea ice remains stationary, and its thickness is controlled by thermodynamic factors only. That ice is termed ‘fast ice’. In those regions, horizontal ice thickness variations are small, typically 10–20 cm within a scale of kilometres. Most of the monitoring data, in particular for ice thickness, have been collected from the fast-ice regions. The record for measured fast-ice thickness is 1.22 m from Tornio, Finland.

Ice thickness in the drift ice regions is much more variable. Drift ice is a mixture of different ice types, and within a scale of kilometres, ice thickness can vary from a few centimetres of thin new ice up to thick pressure ridges. Ice ridges, formed by compressive ice motion, are typically 3–5 m thick, but freely floating ridges 25 m thick have been observed in the Baltic Sea. Ice thickness measurements in drift ice areas have been made during several field campaigns, but the observations are too sparse in time and space to examine long-term change.

The state of sea ice depends on the surface energy balance, momentum flux and water flux. Some of the climate-related state variables, such as ice extent or freezing date, are mainly driven by the energy balance, and the observed variation in these variables very closely reflects large-scale variation in air temperature. However, many variables, such as ice thickness, ice type and duration of the ice-covered period, are also very dependent on winds and ocean currents and may reflect changes occurring at a local scale: this highlights the importance of a unified analysis of ice parameters for quantifying change in sea ice on a climatological scale. An alternative approach for analysing directly

measured geophysical parameters is to use a particular ‘sea ice index’ as a general indicator of ice conditions. For the Baltic Sea, two methods have been used. Koslowski and Glaser (1995) used an index that describes the mass of sea ice by integrating ice thickness over the sea area in question, while Sztobryn et al. (2009) developed an index based on the normalised length of the ice-covered season of several coastal stations. In the Baltic Sea, all these variables display a large interannual variability and are very closely related to the variability in the large-scale atmospheric circulation (Omstedt and Chen 2001; Jaagus 2006; Vihma and Haapala 2009, see also Chap. 4, Sect. 4.2).

Recent years have highlighted the magnitude of the interannual variability of ice conditions in the Baltic. The winters of 2008 and 2009 were very mild; sea ice formed only in the Bothnian Bay and coastal areas of the Bothnian Sea and Gulf of Finland. The MIB was only 49,000 km² in 2008 and 110,000 km² in 2009. The winters of 2010 and 2011, on the other hand, are classed as severe ice winters, and the MIBs were correspondingly larger: 244,000 km² (2010) and 309,000 km² (2011). More importantly, the ice was thick, and severe storms induced pack ice compression events that caused major difficulties for winter navigation. In the past, there have been similar relatively short periods with both extremes of ice conditions, such as 1873–1876, 1938–1941 and 1985–1990. It is also evident that there is no correlation between consecutive ice seasons, simply because the thermal memory of the Baltic Sea is only 2–3 months (Leppäranta and Myrberg 2009).

The first Baltic Sea assessment (BACC Author Team 2008) concluded that climate warming can be detected from the time series of MIB and ice season length. This conclusion was based on studies utilising observations that extended only until 2000. The present review is an updated analysis and includes observations up to 2011. Observed trends in sea ice parameters are summarised in Table 8.1.

8.2 Ice Extent

Annual MIB is the most widely used indicator of sea ice changes because it integrates the winter period weather over the entire Baltic Sea basin (Fig. 8.1). The time series is based on various observation methods. The early part of the time series has considerable uncertainty. It is mainly based on correlation between air temperature recordings, observations from lighthouses, information from newspapers and records of travels on ice (Jurva 1937; Palosuo 1953; Seinä and Palosuo 1996). According to Jurva (1952), MIB has been fairly accurately determined from 1880 onwards from notes made onboard ships navigating in the middle parts of the Baltic Sea during winter (Vihma and Haapala 2009).

Table 8.1 Trends in the annual maximum sea ice extent (MIB), annual maximum sea ice thickness (MIT) and duration of the ice season (DIS), updated summary table based on Vihma and Haapala (2009)

	Region	Period	Trend	Statistical significance	Source
MIB	Baltic Sea	1901–1995	–	No (<90 %)	Haapala and Leppäranta (1997)
MIB	Baltic Sea	1720–1995	–	Yes (97 %)	Haapala and Leppäranta (1997)
DIS	Polish coast	1896–1993	–	Yes	Sztobryn (1994)
DIS	Szczecin Lagoon	1888–1995	–	Yes	Girjatowicz and Kozuchowski (1999)
DIS	Finnish coast	1889–1995	–	Yes (99 %)	Haapala and Leppäranta (1997)
DIS	Finnish coast	1950–2010	–	NR	Ronkainen (2013)
DIS	Port of Tallinn	1500–2000	–	NR but evident since mid-1800s	Tarand and Nordli (2001)
DIS	West Estonian archipelago	1949–2004	–	Yes	Jaagus (2006)
DIS	Southern coast of the Gulf of Finland	1949–2004	–	No	Jaagus (2006)
DIS	Gulf of Finland and Gulf of Riga	1900–1990	–	NR	Jevrejeva (2000)
DIS	Port of Riga	1529–1990	–	Yes (99.9 %) for severe winters; no for mild and average winters	Jevrejeva (2001)
DIS	Baltic Sea coasts	1900–2000	– and +	Depends on station	Jevrejeva et al. (2004)
MIT	Baltic Sea coasts	1900–2000	– and +	No	Jevrejeva et al. (2004)
MIT	Gulf of Bothnia	1899–1995	+ (Kemi) – (other)	Yes (Kemi) No (other)	Haapala and Leppäranta (1997), Launiainen et al. (2002)
MIT	Finnish coast	1950–2010	+ (Kemi) – (Loviisa)	NR	Ronkainen (2013)
MIT	Gulf of Bothnia	1980–2000	–	NR but evident	Launiainen et al. (2002)
MIT	Northern Gulf of Finland	early 1900–1990s	–	NR	Alenius et al. (2003)

– decreasing trend; + increasing trend; *NR* statistical significance of the trend not reported

The MIB displays large year-to-year natural variability due to the large-scale variation in atmospheric circulation, commonly described by the North Atlantic Oscillation (NAO, see Chap. 4, Box 4.1). Vihma and Haapala (2009) used the mean January–March NAO index in their analysis and showed that during a negative NAO phase ($NAO < -0.5$), the mean MIB is 259,000 km² (range: 150,000–405,000 km²), while during a positive NAO phase ($NAO > +0.5$), the mean MIB is 121,000 km² (range: 45,000–337,000 km²) (Fig. 8.2).

In spite of the obvious correlation between the NAO and MIB, in some NAO-positive winters, sea ice extent has been greater than average. In the middle of winter, the heat content of the Baltic Sea is already low, and a long-lasting blocking situation could cause an anomalously cold period and extensive ice growth. Interestingly, the relationship between the NAO index and MIB has not remained constant over time (Omstedt and Chen 2001; Janssen 2002; Schrum and Janssen 2002; Chen and Li 2004). Meier and Kauker (2002) found that during two periods, around 1926 and

1966, the correlation increased simultaneously with improvements in the observation methods for MIB. Changes in the NAO–MIB relationship can, however, also be due to changes in the location of the atmospheric pressure patterns (Koslowski and Loewe 1994; Chen and Li 2004).

All previous studies have reported a significant decreasing trend in MIB (BACC Author Team 2008; Vihma and Haapala 2009). Including observations until 2011, the trend in MIB for the past 100 years is $-3400 \text{ km}^2 \text{ 10 year}^{-1}$ or $\sim 2 \% \text{ 10 year}^{-1}$ (Fig. 8.3). Another apparent change is a fall in the frequency of severe winters over the past 20 years. Figure 8.4 shows that the modal probability of the MIB has remained the same whether the period considered is the past 100, 30 or 20 years, but mild ice seasons have become more common, and years when the Baltic Sea is almost completely ice-covered have not occurred over the past 25 years.

Schmelzer et al. (2012) examined changes in the probability of sea ice occurrence in the southern Baltic Sea. Figure 8.5 compares results for two 30-year periods, 1961–1990 and 1981–2010, and shows a general tendency

Fig. 8.1 Maximum ice-cover extent in the Baltic Sea (MIB), 1720–2012. The *dashed bars* represent the error range of the early estimates. The 30-year moving average is indicated by *two lines* representing the error range early in the series, converging into one line when high-quality data became available

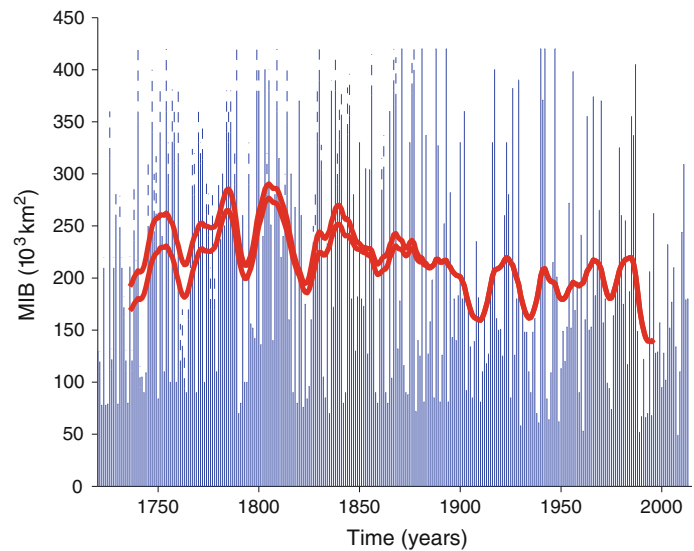
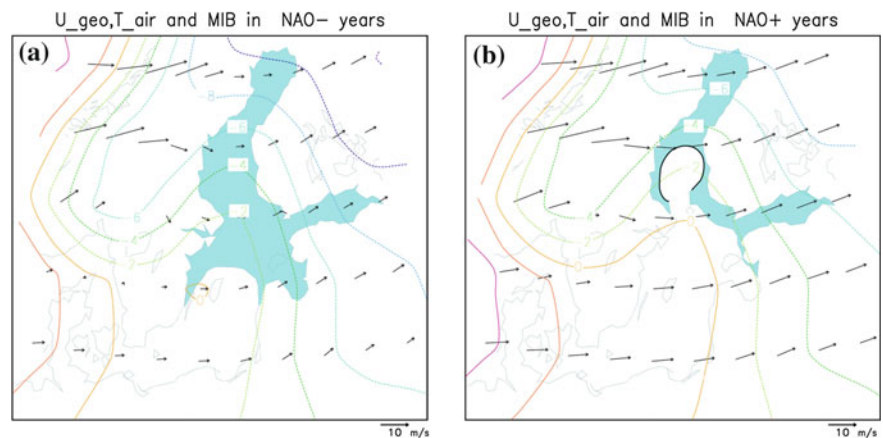


Fig. 8.2 Mean annual maximum sea ice extent (*blue*), 2-m air temperature (*coloured isolines*) and 10-m wind vectors over the Baltic Sea region during two phases of the North Atlantic Oscillation: a negative phase (NAO < -0.5) and a positive phase (NAO > +0.5) (redrawn from Vihma and Haapala 2009)



towards ice-free winters. Major changes have occurred in the offshore area of the western Baltic Sea and east of Bornholm Island, with the lowest frequency of ice occurrence observed

in the past 30 years. There has been a concomitant decrease in the frequency of ‘difficult’ ice conditions (coverage > 7/10 and thickness > 10 cm).

Fig. 8.3 The maximum extent of sea ice cover in the Baltic Sea, 1900–2012. The *red line* shows a long-term declining trend of ~2 % per decade

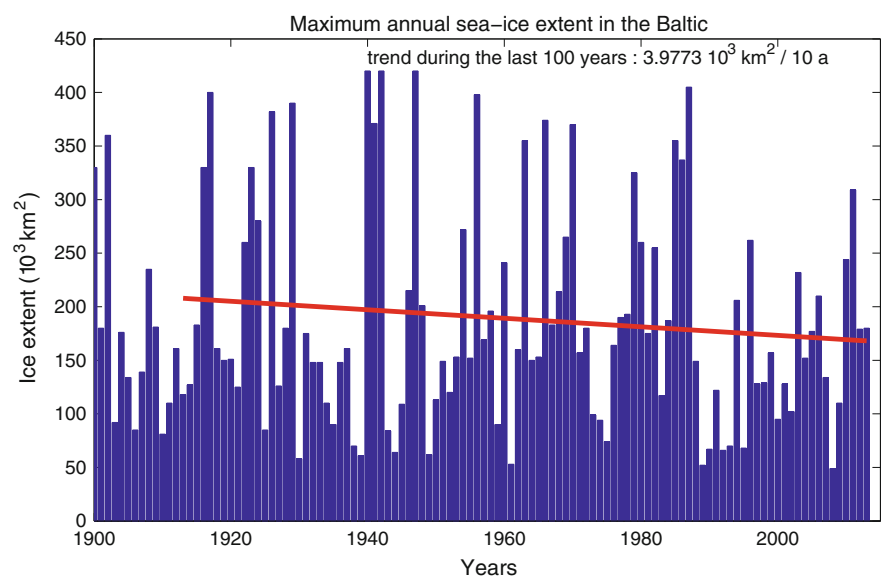


Fig. 8.4 Probability distributions of maximum sea ice extent in the Baltic Sea during 1911–2011, 1981–2011 and 1991–2011

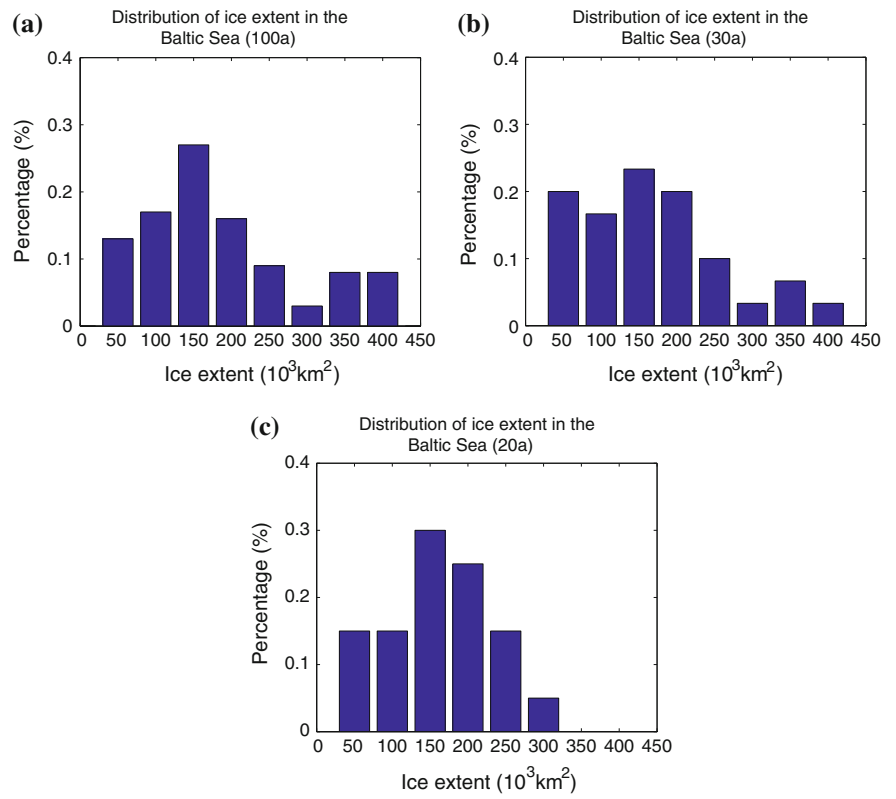
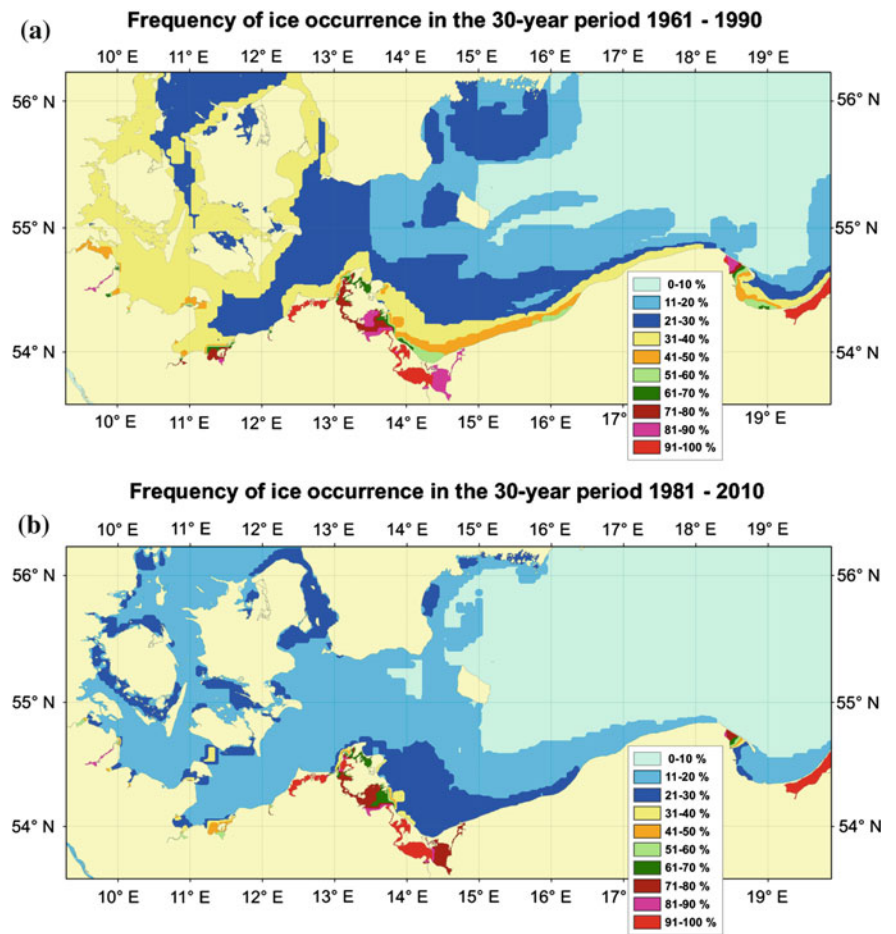


Fig. 8.5 Probability of sea ice occurrence in the southern Baltic Sea (Schmelzer et al. 2012)



8.3 Ice Duration

Jevrejeva et al. (2004) has compiled the most extensive analysis of ice season changes in the Baltic Sea to date, using time series at 37 coastal stations from the Bothnian Bay to the Arkona Basin. In general, observations showed a tendency towards milder ice conditions. For the variables studied, the greatest change occurred in ice season length, which has decreased by 14–44 days over the past 100 years, mostly due to earlier ice break-up.

A recent study by Ronkainen (2013) confirmed the trend towards a shorter ice-covered period in the Finnish coastal zone (Fig. 8.6 and Table 8.2). In the Bothnian Bay (Kemi), where the ice season is clearly longer than in the eastern Gulf of Finland (Loviisa), the trend is $-18 \text{ d } 100 \text{ year}^{-1}$. In the eastern Gulf of Finland, where sea ice is also formed every winter, larger changes have been observed. The length of the ice season has decreased by $41 \text{ d } 100 \text{ year}^{-1}$, while the trend based on the last 50 observations is $-62 \text{ d } 100 \text{ year}^{-1}$.

In the southern Baltic Sea, the first sea ice is formed in the coastal lagoons between 10 and 20 December, near the coast around 1 January, in the sea area of the western Baltic and off the Polish coast in mid-January, and in the German coastal areas at the beginning of January (Schmelzer et al. 2008, 2012; Girjatowicz 2011). Comparing the different periods analysed, there has been no major change in the average date at which ice formation begins (Fig. 8.7). In terms of ice break-up, on average, the last ice in the inner coastal waters has disappeared by late February or early March, while residual ice has been observed in offshore waters until mid-March. The longest duration of ice in the coastal waters was observed in the 1961–1990 winters. In the past 30-year period, ice disappeared from the eastern

coastal waters up to ten days earlier. In the Baltic Sea offshore waters, no change has been observed in this parameter, and in the western Baltic Sea, there has even been a weak trend towards a later break-up date.

Ice duration decreases from east to west, and from the inner waters towards the sea areas. A weak trend towards shorter ice duration was found for the 1981–2010 period. The maximum ice duration occurs in particularly cold and long winter periods. There has been at least one cold winter with strong ice formation in each of the 30-year periods analysed, for example 1962/63, 1978/79 and 1995/96. A significant decrease (30 days) has only been observed in the sea area west and east of Bornholm Island in the period 1971–2000. For the period 1981–2010, ice duration during very cold winters is nearly identical to that in 1971–2000.

8.4 Ice Thickness

For climate studies, the sea ice thickness or, preferably, the large-scale sea ice thickness distribution should be the main indicator of change in sea ice, since it is essentially the same as the mass of the ice pack. However, interpreting the causes of change in sea ice thickness is not straightforward, since in addition to the atmosphere–ocean energy balance, sea ice thickness depends on snow thickness and ice dynamics.

Monitoring activity in the Baltic Sea is limited to the land-fast ice regions, where the sea ice could be thinner than in the drift ice regions. According to Jevrejeva et al. (2004), the ice thickness time series around the Baltic Sea coast does not show any consistent trend: both decreasing and increasing trends were reported. A recent study by Ronkainen (2013) supported these conclusions. In the Bothnian Bay (station

Fig. 8.6 Observed changes in **a** length of ice season in Kemi and **b** in Loviisa, and **c** ice thickness in Kemi and **d** in Loviisa (Ronkainen 2013)

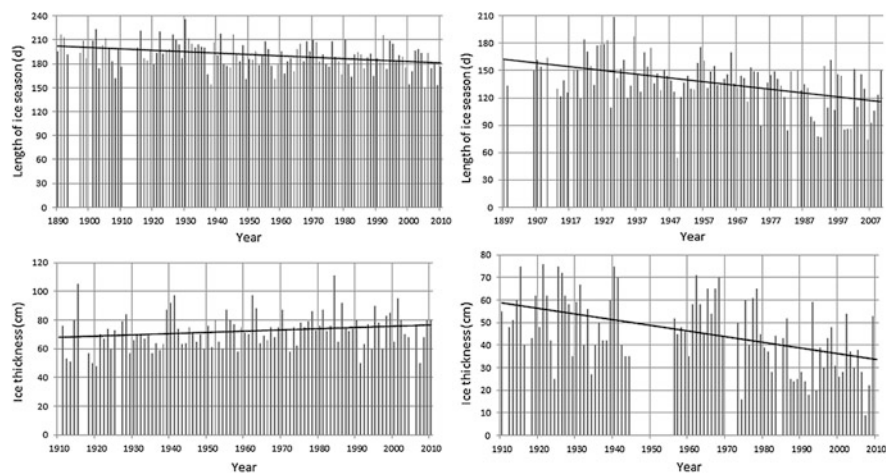


Table 8.2 Change in freezing date, break-up date, length of ice season and ice thickness in the Finnish coastal zone of the Baltic Sea

		Kemi, Bothnian Bay	Utö, Archipelago Sea	Loviisa, Gulf of Finland
Freezing date	Probability of ice appearance	1.00	0.81	1.00
	Trend 100 year ⁻¹	0	-0.19	0
	Number of observations	112	97	106
	Mean date	10 Nov	27 Jan	7 Dec
	Trend (days 100 year ⁻¹)	7	(24)	20
	Trend pre-1950 (days 100 year ⁻¹)	12	(65)	25
Break-up date	Trend post-1950 (days 100 year ⁻¹)	0	(-15)	24
	Number of observations	113	97	10
	Mean date	20 May	9 Apr	24 Apr
	Trend (days 100 year ⁻¹)	-11	(-16)	-20
	Trend pre-1950 (days 100 year ⁻¹)	-5	(-1)	-8
Length of ice season	Trend post-1950 (days 100 year ⁻¹)	-17	(-34)	-38
	Number of observations	113	121	102
	Mean (days)	190	50	137
	Trend (days 100 year ⁻¹)	-18	-46	-41
	Trend pre-1950 (days 100 year ⁻¹)	-17	-84	-32
Ice thickness	Trend post-1950 (days 100 year ⁻¹)	-16	-36	-62
	Number of observations	94		81
	Mean (cm)	73		46
	Trend (cm 100 year ⁻¹)	9		-25
	Trend pre-1950 (cm 100 year ⁻¹)	13		-29
	Trend post-1950 (cm 100 year ⁻¹)	4		-52

Data for three sites: Kemi (1890–2010), Utö (1889–2010) and Loviisa (1894–2010) (Ronkainen 2013). The parentheses indicate values that are not based on all data because the probability of ice occurrence is less than one

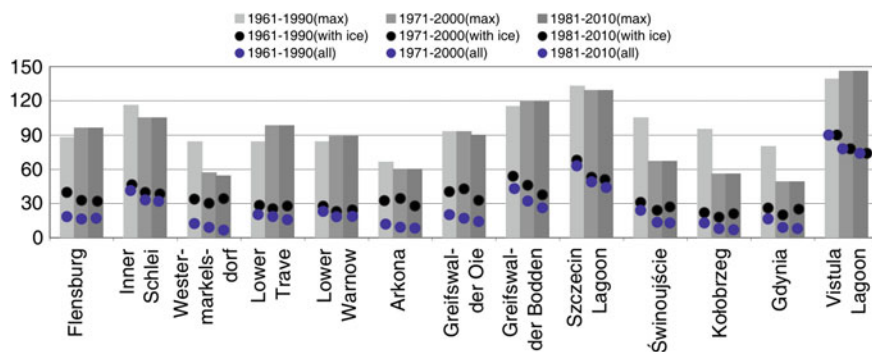


Fig. 8.7 Mean number of days with ice (all winters), mean number of days with ice (only winters with ice) and maximum number of days with ice on the southern Baltic Sea coast in the 30-year periods 1961–1990, 1971–2000 and 1981–2010 (Schmelzer et al. 2012)

Kemi), ice thickness shows a slight increasing trend (+9 cm) over the past 100 years, while in the Gulf of Finland, a thinning trend is observed (-25 cm).

In the southern Baltic Sea, ice thickness in the sheltered coastal waters reached 10–20 cm on average, and as much as 40–62 cm in the extremely hard ice winter of 1962/63 (Fig. 8.8). In most parts of the Baltic Sea offshore waters, ice thickness reaches 5–20 cm, but in particularly cold and long

winters, the ice grows to 50 cm thickness in some areas. A maximum ice thickness of 70 cm was reached in the Kiel and Lübeck bays and in the waters of Rügen in the winter of 1962/63. In Szczecin Lagoon, in the Bay of Puck and in Vistula Lagoon, the ice reached 62 cm thickness. Since 1971, the maximum ice thickness has been about 50 cm in the southern Baltic Sea coast and up to 30 cm in the sea area north of Rügen.

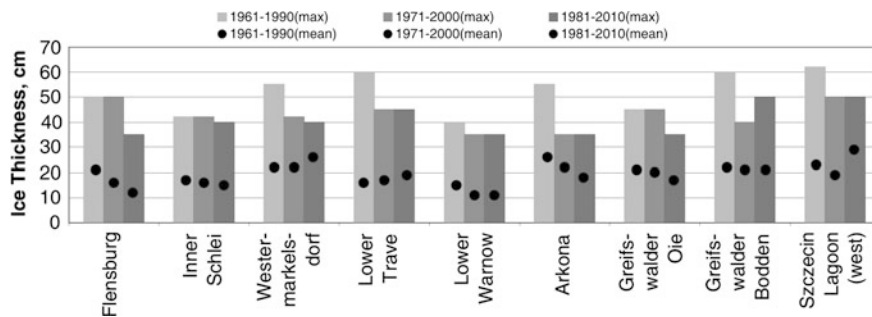


Fig. 8.8 Mean and extreme annual maximum ice thickness (for winters with ice only) on the German Baltic Sea coast within the 30-year periods 1961–1990, 1971–2000 and 1981–2010 (Schmelzer et al. 2012)

8.5 Conclusion

Sea ice conditions in the Baltic Sea have been systematically monitored for more than a century. All sea ice-related parameters display large interannual variability, but a change towards milder ice winters has been observed over the past 100 years: in particular, the annual maximum ice extent has decreased, and the length of the ice season has become shorter. Interannual variability in sea ice conditions is principally driven by the large-scale atmospheric circulation. In particular, the winters of strong westerly circulation, that is during positive phases of the NAO, have manifested as a minimum ice cover in the Baltic Sea. However, a winter without any ice formation in the Baltic Sea is far from the present climatology. According to some 300 years of records of annual maximum sea ice extent, the northernmost sub-basin, the Bothnian Bay, has been entirely ice-covered even during the mildest winters, and the length of the ice season near the coast has been 150 days at a minimum.

In addition to a tendency towards milder winters, the occurrence of severe ice winters, when the southern Baltic Sea is ice-covered, has also decreased considerably over the past 25 years. Although these observations are consistent with the changes in global climate, ice season length declined to a similar extent during the first half of the twentieth century, when anthropogenically derived greenhouse gas emissions are likely to have had almost no impact on climate. Long-term changes in the Baltic Sea regions have been interpreted as the result of a recovery from the ‘Little Ice Age’ (Omstedt et al. 2004), but changes in sea ice could also be due to shipping. Motivation for sea ice measurements has been the provision of data for shipping, and consequently, monitoring sites have typically been located near harbours. Ship-induced waves are known to prevent the formation of a permanent ice cover in autumn and also to enhance break-up of the ice cover in spring, and so an increase in the size of vessels and the intensity of shipping activity could also affect local ice conditions.

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