Chapter 4
Changes in Sea-Ice Extent and Thickness in Kongsfjorden, Svalbard (2003–2016)

Olga Pavlova, Sebastian Gerland, and Haakon Hop

Abstract Seasonal sea ice is an important feature in Svalbard fjords for both the physical environment and the ecosystem. Systematic sea-ice monitoring in Kongsfjorden, Svalbard, as a part of a long-term project conducted by the Norwegian Polar Institute (NPI), was started in 2003. The inner part of Kongsfjorden is usually covered by seasonal fast ice initially forming between December and March and persisting until April–June. Before 2006, the sea ice typically extended into the central part of the fjord, but during the last decade the sea-ice extent has often been reduced to the northern part of the inner bay. Two exceptions were 2009 and 2011, when the ice extent was similar to earlier years. The minimum record for spring ice extent within the observed period was in 2012, when sea ice was only present in the northern part of the inner bay. Maximum seasonal thickness of fast ice was around 0.6 m or more prior to 2006, declining to about 0.2 m in recent years. The snow thickness on fjord fast ice declined from around 0.2 m in spring prior to 2006 to <0.05 m in recent years, which reflected the shorter duration of ice cover. Advection of Atlantic water into Kongsfjorden, particularly during the winters of 2006–2007, contributed to reduced fast-ice formation. This, in combination with relatively mild winters, can be seen as main factors for changing fast-ice conditions in Kongsfjorden during the last 10 years. Sea-ice extent and seasonal duration have important implications for the marine ecosystem in Kongsfjorden with regard to pelagic and benthic production as well as selected species of seabirds and marine mammals.

Keywords Kongsfjorden · Svalbard · Sea ice · Time series · Ecosystem effects · Climate change

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4.1 Introduction and Motivation

Sea-ice conditions around Svalbard, in particular sea-ice extent, ice-edge configuration and ice concentration, are controlled or influenced by the regional conditions, such as the geographical setting of Svalbard, the sea-floor topography and the patterns and properties of the regional ocean currents (Walczowski et al. 2012, 2017). Svalbard is situated adjacent to both Arctic and Atlantic water masses, and the sea ice is influenced by warm, saline water on its way from the Atlantic to the Arctic Ocean along the western coast of Svalbard (West Spitsbergen Current, a branch of the North Atlantic Current), and cold, less saline water from the Arctic to the Atlantic along the eastern coast of Svalbard (Svendsen et al. 2002). The latter current continues around the cape Sørkapp and prevails as a coastal current on the shelf along West Spitsbergen. Thus, Atlantic water mixes with Arctic water on the shelf and is advected into the open fjords as Transformed Atlantic Water (Cottier et al. 2005, 2010; Hop et al. 2006; Nilsen et al. 2016). The archipelago, located at the relatively high latitude of 77–80°N, features an Arctic climate. However, these two currents have strong control on the local climate and the winter sea-ice distribution. In particular, the West Spitsbergen Current creates a warmer climate on the west coast of Spitsbergen than in other regions at similar latitudes (i.e., Canadian and Russian Arctic) (Orvik and Niiler 2002; Loeng and Drinkwater 2007; Nilsen et al. 2008; Skagseth et al. 2008, 2011; Cottier et al. 2010; Smedsrud et al. 2011, 2013).

The West Spitsbergen Current reaches the western coast and northern shelf of Spitsbergen, keeping water open and navigable most of the year along the southern part of the west coast. The sea ice around Svalbard is commonly composed of first-year ice and various young ice classes. Multiyear sea ice can appear, transported from the Arctic Basin, especially north and east of Svalbard (e.g., Kwok et al. 2005; Kwok 2009; Onarheim et al. 2014). Fast ice in fjords of western Spitsbergen (e.g. Kongsfjorden and van Mijenfjorden) grows less thick than ice in fjords that are less or not at all influenced by Atlantic water (e.g. Rijpfjorden and Storfjorden), see e.g. Gerland et al. (2008, their Fig. 4.3). Maximum fast-ice thicknesses observed in five Svalbard fjords during winter 2006/07 showed variable thickness from 20 cm in Grønfjorden (part of the Isfjorden system, near Barentsburg) to 66 cm in van Mijenfjorden. The two fjords further east, Storfjorden (Inglefieldbukta, 90 cm) and Rijpfjorden in the northeast (114 cm) had much thicker ice.

Surface snow (snow on ice) and ice growth/melt are important elements of evolution of the ice cover, and weather conditions (air temperature, precipitation and wind) play a main role in this process. Additionally, the ice surface topography is also important for ice and snow growth (see e.g. Nicolaus et al. 2003; Cheng et al. 2008, 2014; Wang et al. 2015).

Formation and evolution of sea ice in Kongsfjorden integrate many atmospheric, oceanic and terrestrial factors, such as air and water temperature, advection of the warm Atlantic water, reorganisation of atmospheric pressure fields and water circulation, winter convection, precipitation (amount, timing) and snow cover, and freshwater runoff from glaciers and rivers (Gerland et al. 1999; Cottier et al. 2005, 2007, 2010; Gerland and Renner 2007).

About 80% of the drainage area in Kongsfjorden is glacier-covered (J. Kohler, Norwegian Polar Institute, unpubl. data). Kongsfjorden is strongly influenced by the tidewater glaciers Kronebreen and Kongsvegen at the head of Kongsfjorden, and Conwaybreen and Blomstrandbreen on its northeastern and northern coasts (Lefauconnier et al. 1994; Trusel et al. 2010; Köhler et al. 2012; Nuth et al. 2012, 2013; Luckman et al. 2015; Schellenberger et al. 2015). During summer (with peak run-off in late July and August), they contribute sediments and freshwater in liquid form and calving of icebergs (Svendsen et al. 2002; Sundfjord et al. 2017; Tverberg et al., Chap. 3). Grounded and drifting icebergs and smaller pieces of ice influence the formation of fast ice by forming fixed points that keep the fast ice in place leading to locally increased or reduced accumulation of snow (Lydersen et al. 2014).

Monitoring of the sea-ice conditions in Kongsfjorden can be used to demonstrate and investigate phenomena related to climate change in the Arctic. Consistent studies of the sea-ice conditions in Kongsfjorden, including monitoring of fast-ice evolution and sea-ice thickness started in the late 1990s. Some sporadic information on fast-ice extent before the mid-1990s exists from biological studies (Lydersen and Gjertz 1986; Mehlum 1991; Parker and Mehlum 1991; Smith and Lydersen 1991). However, these references deal mainly with the ice-associated biota at higher trophic levels and only secondarily with sea-ice extent, and not with its thickness. Snow and ice thickness, physical ice properties and the development of superimposed ice in Kongsfjorden have been investigated more intensively since 1997 (Gerland et al. 1999, 2004, 2008; Svendsen et al. 2002; Nicolaus et al. 2003; Gerland and Hall 2006; Gerland and Renner 2007; Willmes et al. 2009). In particular, physical parameters and surface processes of fast ice in Kongsfjorden for the years 1997, 1998, 2002 and 2003 have been reviewed by Gerland et al. (2004) based on the results of Gerland et al. (1999), Nicolaus et al. (2003), Hamre et al. (2004) and Winther et al. (2004). Different aspects of sea ice were addressed by Gerland et al. (2004), including the development of sea-ice concentration, snow and ice thickness, texture of snow and ice, salinity and temperature, and spectral surface reflectance and albedo during the period from late winter to summer, and they also investigated fast-ice formation, development and decay.

Systematic fast-ice monitoring for Kongsfjorden, as a part of a long-term project at the Norwegian Polar Institute (NPI), was started in 2003. It includes mapping of sea-ice extent and *in situ* measurements of ice and snow thickness, and freeboard at several sites in the fjord. Data collected within this standardized monitoring programme have contributed to a number of studies. A comprehensive analysis of fast-ice evolution in Kongsfjorden (2003–2005) was given by Gerland and Renner (2007), which included quantitative estimates of the fast-ice mass balance in the fjord. Due to increased activities in the framework of the International Polar Year (IPY), more intensive fjord ice studies were performed in several of the Svalbard fjords. This gave a good opportunity to compare the fast-ice evolution in Kongsfjorden with that of other Svalbard fjords (e.g. Gerland et al. 2008; Hendricks et al. 2011; Zhuravskiy et al. 2012; Renner et al. 2013a, b; Wang et al. 2013; Ivanov et al. 2014). For example, Zhuravskiy et al. (2012) analysed the long-term variability of ice characteristics (based on visual and instrumental observations), as well as main oceanographic and meteorological characteristics, in Grønfjorden from 1974 to 2008. The authors reported that, due to the geographical and climatic features of the region, the beginning of stable ice formation varied significantly from year to year, but generally occurred from mid-December to early January. The maximum thickness of fast ice also showed strong variability, with the maximum ice thickness (0.93 m) measured in 1986. Their results also indicate a tendency toward a response of fast ice to a milder climate during the last decades of the 20th and the beginning of 21st century in Grønfjorden.

In this review, we summarize published results, and we present new observational data of ice extent, and ice and snow thickness in Kongsfjorden. This includes a time-series of sea-ice measurements from 2003 to 2016. Changes in sea-ice conditions have implications for the marine ecosystem in Kongsfjorden, from the primary producers of ice algae and phytoplankton to upper trophic levels including seabirds and marine mammals (e.g. Hanssen et al. 2013; Lydersen et al. 2014; Vihtakari et al. 2018). Ecological changes in different compartments of the Kongsfjorden system, partly because of changes in sea ice, have been addressed in other chapters in this book (e.g. Fredriksen et al., Chap. 9; Hegseth et al., Chap. 6; Molis et al., Chap. 11). Because this paper focuses on long-term changes in sea ice, we are limiting the discussion to some of the main ecological implications of reduced sea ice in Kongsfjorden.

4.2 Research Area

Kongsfjorden is located at about 79°N, 12°E on the west coast of Spitsbergen (Fig. 4.1a, b). The fjord is about 25 km long and 5–10 km wide. Characteristic landmarks for Kongsfjorden are: Brandalpynten, a cape just west of Ny-Ålesund; Blomstrandhalvøya, the largest island in Kongsfjorden, north of Ny-Ålesund near the northern shore of the fjord; the archipelago Lovénøyane in the inner fjord, with Storholmen as the largest and westernmost island; Dyrevika, the bay in the northern inner fjord; and several glaciers terminating in the fjord, among them Kongsvegen and Kronebreen (glaciers with one of the highest flux rates on Svalbard) and Kongsbreen (the most active calving glacier on Svalbard) in the innermost part of fjord.

The physical environment, including the hydrography of Kongsfjorden, has been described in several publications (see e.g. Haugan 1999; Svendsen et al. 2002; Cottier et al. 2005, 2010; Prominska et al. 2017) and also more briefly by Gerland and Hall (2006) and Gerland and Renner (2007). Kongsfjorden and Krossfjorden (fjord arm to the north) are hydrographically connected by the Kongsfjordenrenna to the North Atlantic, and receive warm Atlantic water masses from the West Spitsbergen Current, which is the main cause of the late onset of ice formation each winter. Atlantic water enters Kongsfjorden along the southern coast and mixes with

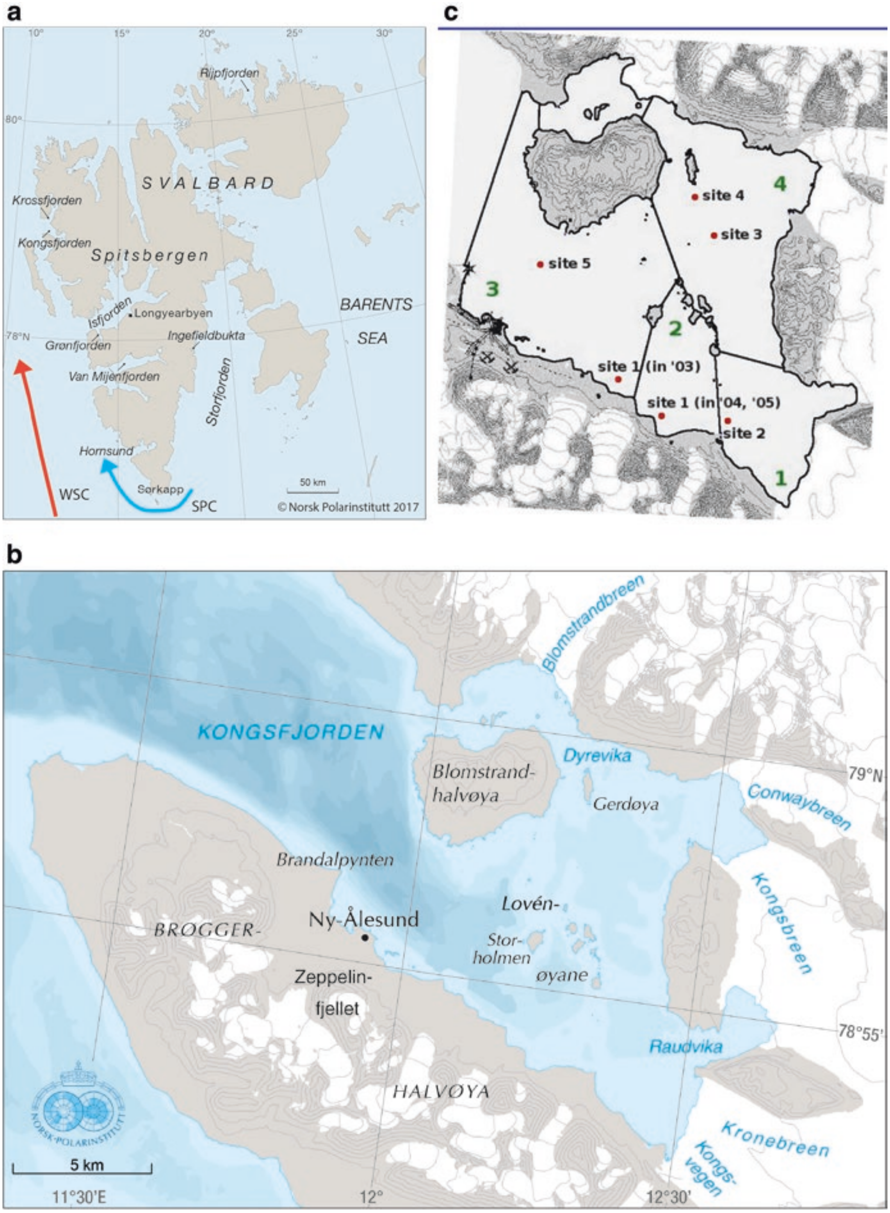


Fig. 4.1 Map of (**a**) Svalbard area. WSC – West Spitsbergen Current, SPC – Spitsbergen Polar Current (coastal current); (**b**) Kongsfjorden; (**c**) Inner part of Kongsfjorden with sectors 1–4 (labelled with green numbers) and monitoring sites. (From Gerland and Renner 2007)

meltwater and runoff water in the inner part, before it exits the fjord on the northern edge, partly via Krossfjorden. The wide mouth of the fjord, with Krossfjorden to the north, enables ocean swells from storms to reach the central part of the fjord, and this can break up the fast ice (Tverberg et al., Chap. 3).

4.3 Methodology

Conception and methodology of the systematic fast-ice monitoring in Kongsfjorden are described in Gerland and Hall (2006) and Gerland and Renner (2007) and include observations and quantification of sea-ice extent and *in situ* measurements of ice and snow thickness, and freeboard. Both types of observation results are needed for quantitative sea-ice mass-balance estimates and for characterization of the ice situation, for example in terms of stability against destruction by waves or after being affected by mild spells during winter (Gerland and Renner 2007). The monitoring was designed to be relatively inexpensive, robust, and consistent over time. However, consistency can be a challenge given the changing conditions of the matter that is being monitored. The permanent presence of staff at the research base of Sverdrup Station (Norwegian Polar Institute) and daily visits to the observatory on the mountain Zeppelinfjellet (just south of Ny-Ålesund) enable regular *in situ* thickness measurements and ice observations. The altitude of Zeppelinfjellet (474 m a.s.l.) gives a reasonable overview on the fjord ice situation, but the part north of Blomstrandhalvøya is not visible from there, and details of the ice situation on the innermost parts of the fjords are difficult or impossible to observe.

4.3.1 Sea-Ice Extent

Sea-ice extent data are derived from ice maps and photography. Observations of fast-ice and drift-ice extent are based on visual observations, and, accordingly, no data are available for days when there is limited visibility (low clouds, fog and darkness). An observation area for ice extent in inner Kongsfjorden was defined to be 120 km^2 (Gerland and Renner 2007). In order to account for locally different conditions during ice formation, the observation area was divided into four sectors (Fig. 4.1c).

The maps of observational areas were drawn by hand visually assessing the ice edge, and photographs were taken from Zeppelinfjellet. In maps and from photographs, we classify the ice as "fast ice" and "drift ice", usually either pack ice broken off the fast ice, or ice advected from other areas (Krossfjorden and areas outside Kongsfjorden/Krossfjorden). To calculate the area of sea-ice cover, a polygon covering Kongsfjorden was created using ArcMap (Esri.com). Hand-drawn ice maps for selected dates were digitally superimposed on the polygon. The ice cover was divided into the regions of "fast ice", "drift ice" and "open water", and the area of

Fig. 4.2 Drillhole measurements in Kongsfjorden. (Photo: S. Gerland, Norwegian Polar Institute)

each region was calculated using ArcMap. As the area north of Blomstrandhalvøya is not visible from Zeppelinfjellet, it was excluded from fast-ice extent and mass balance calculations.

4.3.2 Ice and Snow Thickness Measurements

Monitoring sites in inner Kongsfjorden are accessed by snowmobiles or a small boat (Fig. 4.2). Then, measurements are made at some distance from the ice edge to avoid the effects of melting close to the edge. Ice thickness, snow thickness and freeboard are measured conventionally from drill holes, drilled with an auger, using a measurement stick with a notch or a tape-measure thickness gauge (Kovacs Enterprises, USA). Snow thickness is measured with a metal stake with markings. The monitoring usually consists of observations at four to five sites in inner Kongsfjorden. Drillings are made approximately every 2 weeks as long as it is possible to access the sites. At each site on each occasion, three holes are drilled in the corners of a triangle with 10 m side length to account for variability at the site (see also Gerland and Hall 2006). Measurement data from the three holes are later averaged. Locations of sites are measured with GPS. Additionally, a detailed 1-week field campaign has been carried out every year in April or early May close to the maximum sea ice and snow thickness.

4.4 Observations of Ice Extent and Thickness

Observations of ice extent and thickness have been published for Kongsfjorden, but no long-term series with more than a decade of measurements. We here present updated ice-extent results for the period 2003–2016, before detailing updated ice and snow thickness results for the period 1997–2016.

4.4.1 Fast-Ice Extent for the Period 2003–2016

The evolution of fast ice in Kongsfjorden for the period 2003–2005 (the first 3 years of the systematic monitoring) is presented in detail in Gerland and Renner (2007). The fast-ice coverage reached its maximum (120 km^2) within the defined observation area in all 3 years of observations (Fig. 4.3). The entire observation area was ice-covered in March 2003, mid-January 2004 and late February 2005 (Fig. 4.3). The ice cover persisted to late June in 2003–2005. The decay of fjord ice in 2003 stopped up at a level of about 70 km^2 (late May-early June) before it continued further on in June. Similar decay developments can be seen for 2004 and 2005, but with intermediate stagnation levels at about 80 km^2. The ice decay progressed significantly faster in 2005 than in 2004. The second part of the ice-extent decay appeared similar for 2003 and 2004, but 2005 was different, with an earlier ice-free fjord.

The period of 2006–2016 was characterised by relatively little sea-ice cover, except for 2006 and 2011 when the fast-ice coverage reached its maximum (120 km^2) within the defined observation area (Figs. 4.3 and 4.4). The fast-ice formation in Kongsfjorden during this period started in March for most years, except for 2006, 2011 and 2015 when the ice formation started in February, and melting or break-up generally started in April–May (Fig. 4.3). The behaviour of sea-ice evolution in these 3 years was different. Thus, despite the fact that in 2006 and 2011 the entire observation area was ice-covered with fast ice at the end of February, 2006 was characterised by relatively short fast-ice season (mid-February-end of April) and earlier fast-ice decay. On the contrary, the ice-coverage season was long in 2011 (February–June). The year 2015 was characterized by relatively long fast-ice season (mid-February-beginning of June), but little fast-ice cover.

In most years, the ice cover was both less extensive and of shorter duration, except for 2003–2006 and 2011. In 2007, 2012, 2014 and 2016, the southern shore of Kongsfjorden was never properly connected with fast ice in the inner fjord (Fig. 4.3). The edge of fast-ice cover did not reach Lovénøyane in the inner fjord during winters of 2012 and 2014 (Fig. 4.3). The years 2012, 2014 and 2016 were characterized by the lowest sea-ice extent with a very short period of fast ice, from March to April–May. During all years, the fast ice stayed longest in Dyrevika, the bay in the northern part of the inner fjord. However, not all parts of inner Kongsfjorden can be observed from Zeppelinfjellet, so fast ice in Raudvika and the new bay off the northern glacier front of Kongsbreen are also likely to contain fast ice longer than less protected areas.

Maximum fast-ice coverage for each of 5 months (February–June) in the period 2003–2016 shows alternating periods of extensive and little ice cover (Fig. 4.4). Maximum fast-ice cover values (100%) in February were reached in 2005 and 2011. For 2003, we do not have ice-cover information before March, and in 2004 the entire observation area was ice-covered with fast ice in mid-January (not shown). In March, only the years 2003–2005 had 100% fast-ice coverage, while in April, the two largest maximal fast-ice cover values (93% and 80.5%) were observed in 2004 and 2011, respectively. In the other 2 months (May–June), the maximum fast-ice

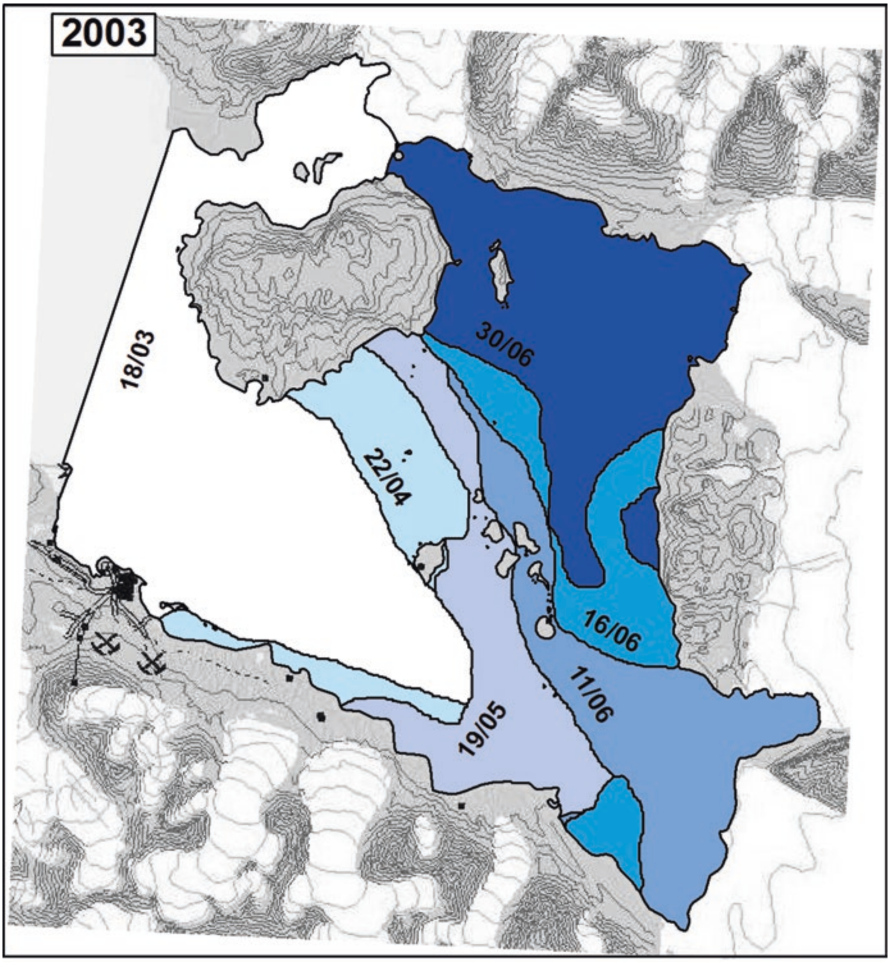
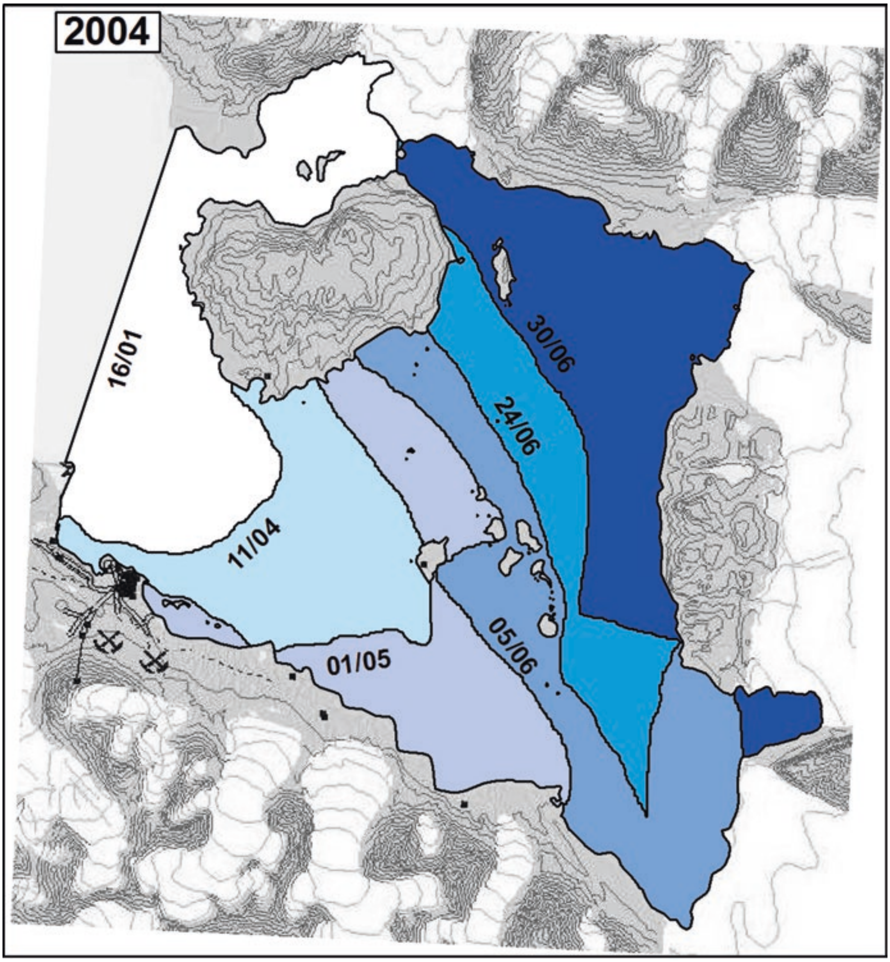


Fig. 4.3 Sea-ice extent for 2003–2005 (from Gerland and Renner 2007) and 2006–2016. Different colours correspond to ice extent on respective dates, and open water (dark blue) is also indicated



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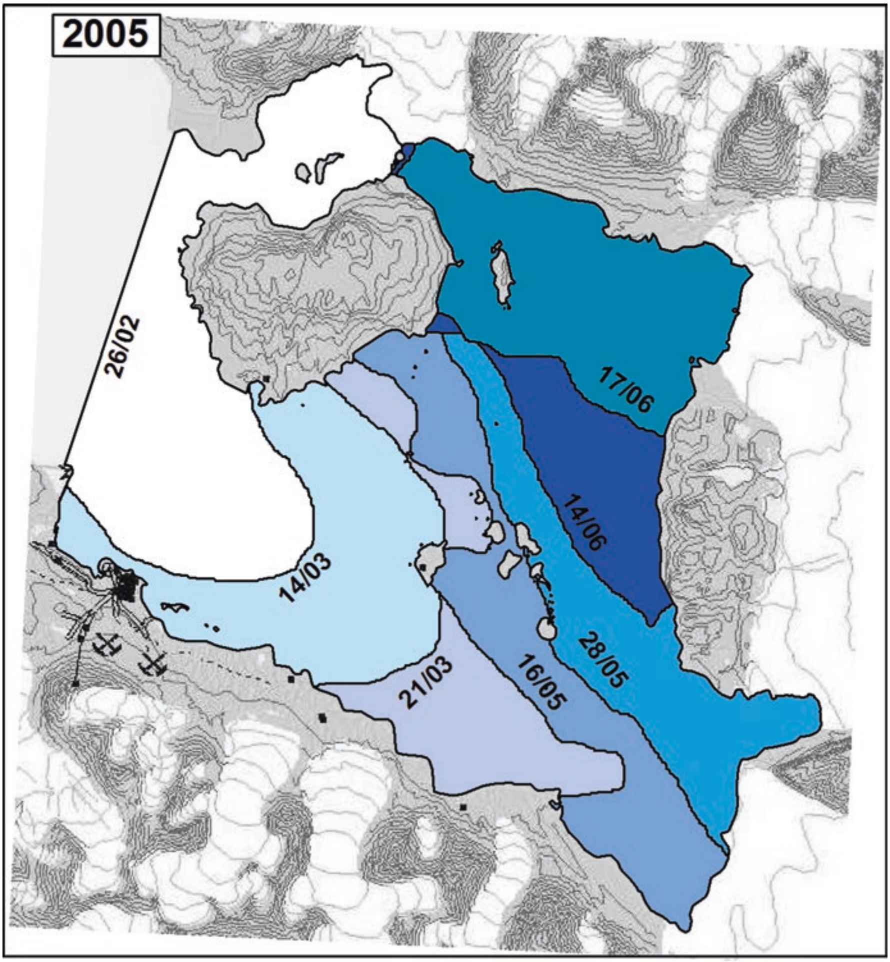
coverage was not higher than 50%, except for the period 2003–2005. Maximum fast-ice coverage of 50% and higher was reached in the years 2003–2006 and 2009–2011 in February–April. During the periods 2007–2008 and 2012–2016, the fast-ice area was <50%, except for February 2008 and 2015 (Fig. 4.4). Both figures (Figs. 4.3 and 4.4) reflect the late ice growth, low coverage and short season of fast ice in the years 2012, 2014 and 2016. Based on conditions from 2003–2016, the fast-ice evolution in Kongsfjorden during this period showed that (i) fast-ice formation scenarios varied annually, but with intervals (2–3 years or more) of relatively high and low sea-ice cover; (ii) most years after 2006 had low ice extent and short season of fast ice.



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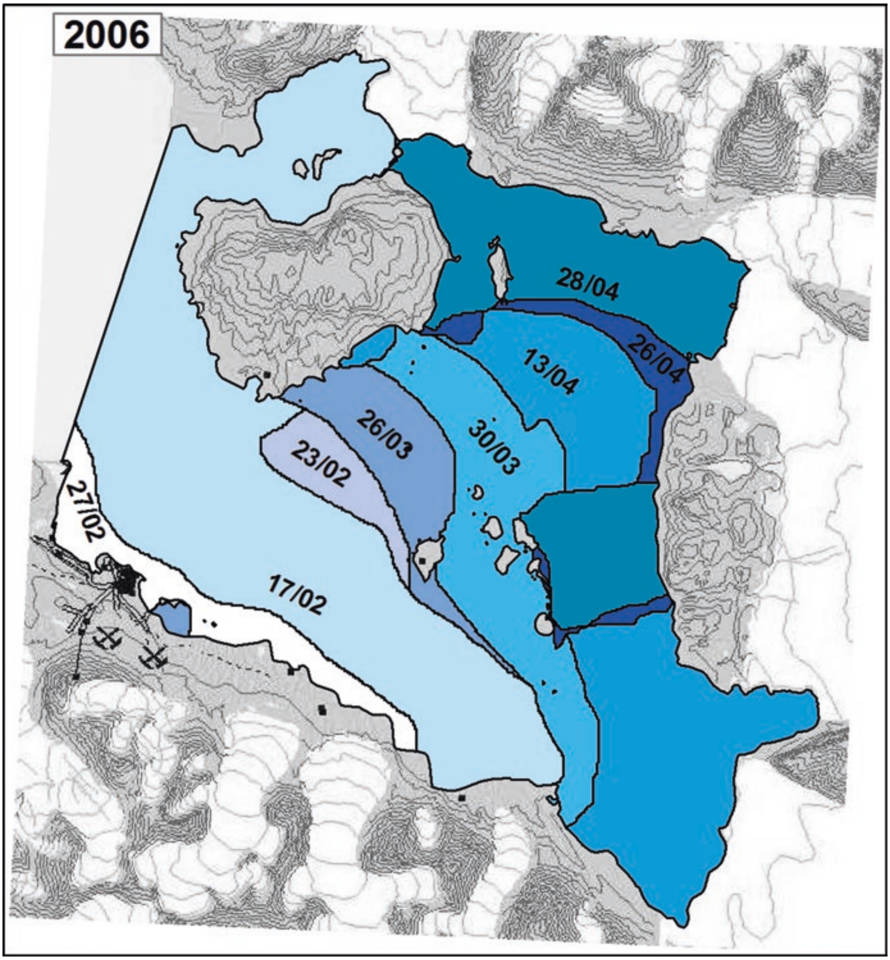
4.4.2 *Ice and Snow Thickness*

Both fast-ice and snow thickness have experienced negative trends over the observation period (1997–2016), towards thinner ice and snow cover. The thickness of fast ice reached seasonal maxima in the range of 0.7 m during the first years of the monitoring period (Fig. 4.5). In recent years, except for 2011, values decreased to around 0.2 m. The linear trend of that change is −24.7% per decade. However, the inter-annual variation in ice thickness appears to be substantial. In parallel to this development, snow thickness decreased from around 0.2 m to <0.05 m, exhibiting an even larger negative trend in relative values with −41.7% per decade. The last 4 years (2013–2016) were all years with very little snow on the sea ice. The analysis further demonstrates that the two variables are related on the inter-annual time



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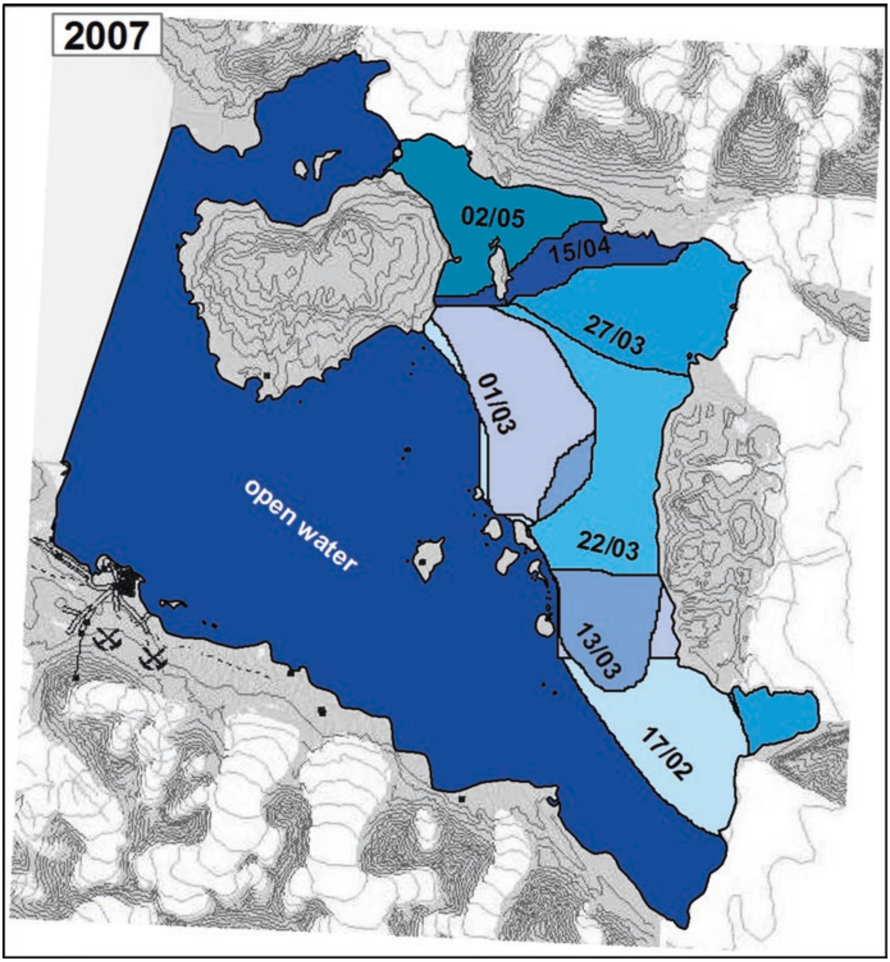
scale. In particular, based on observations for all years our results suggest that the seasonal maximum snow and ice thickness in Kongsfjorden were positively related with $r^2 = 0.42$ (Fig. 4.6). Note that in order to account for the longer-term changes in the two variables they were detrended prior to analysis.

4.4.3 Atmospheric Influence

Among the environmental and physical parameters that strongly influence the fast ice are air and seawater temperature, solar radiation, wind speed and direction, and waves (swell). Cold air and water are an absolute necessity to produce sea ice.



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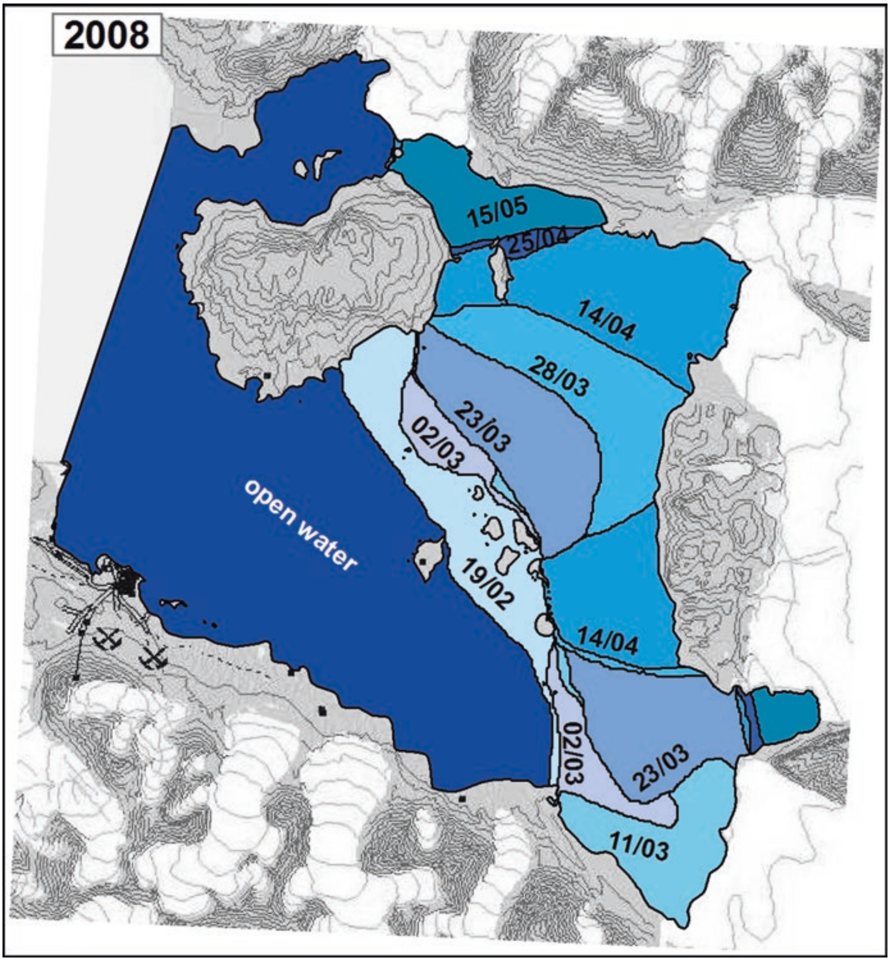
However, often a combination of parameters results in ice formation or decay. The ice-covered area was significantly negatively related to air temperature during winter in Ny-Ålesund, (Table 4.1) with less ice in warmer winters ($r^2 = 0.51$; Fig. 4.7). These two variables were detrended prior to analysis.

Gerland and Renner (2007) showed that daily mean air temperature for Ny-Ålesund in 2005 season was higher than in both 2003 and 2004. During the winter of 2005/2006, the air temperatures showed dramatic changes, and temperature in December 2005 and January 2006 were the highest for 2003–2016 (Table 4.1). In February and March 2006, the temperature was comparatively low but reached high values in April and May. This corresponded with the ice-extent evolution in 2006, which showed relatively short duration and earlier decay compared with the years 2003–2005. The years 2007–2008 had relatively low tempera-



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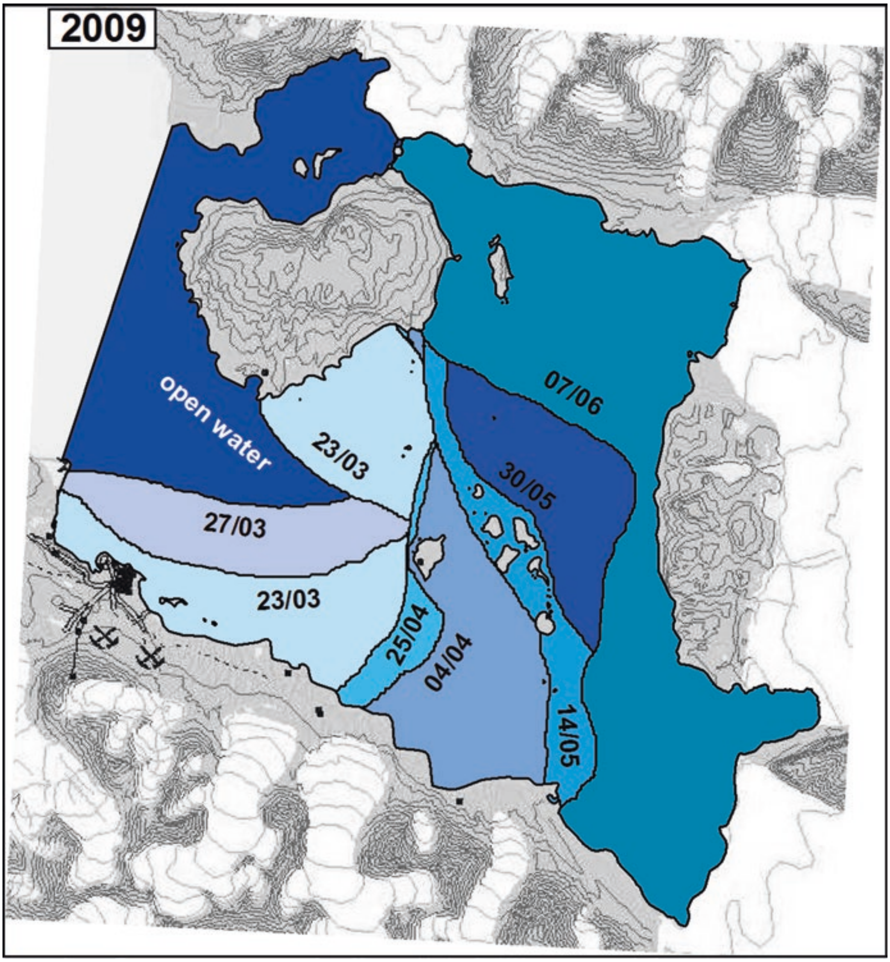
ture in December 2006 and 2007, and in January–April 2007 and 2008. In the years 2009–2011, when the ice extent was relatively high (including the second maximum in 2011), the air temperature was low during all winter-spring months. After 2011, the air temperature became higher during winter (December–March), except for February 2015. Thus, the Kongsfjorden area had two periods of low and high air temperature with corresponding periods of much (2009–2011) and little (2012–2016) fast-ice cover.



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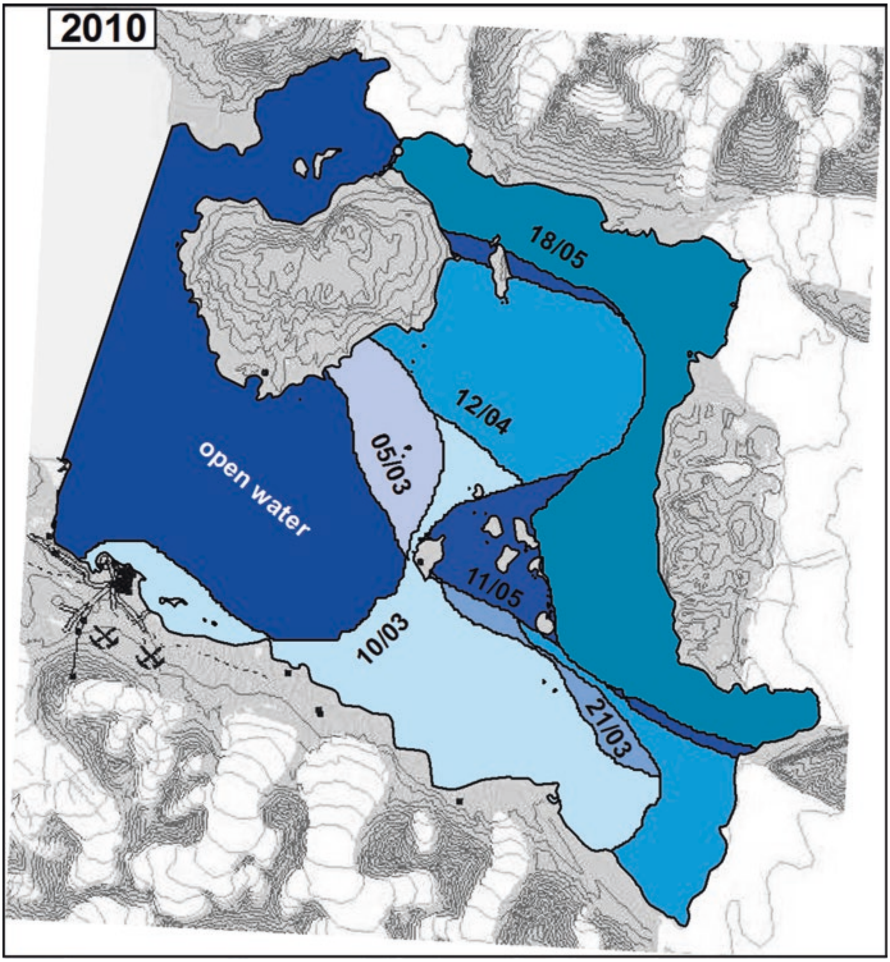
4.5 Discussion and Ecological Implications

Inter-annual variation in fast-ice thickness showed consistent patterns in two studies from Kongsfjorden, conducted during 1997–2005 (Gerland and Hall 2006) and 2003–2005 (Gerland and Renner 2007). The last study included detailed mass-balance observations of fast ice. The fixed geographical setting (coastline, islands) led to a similar ice extent in spring (early May) for all years investigated. The temporal evolution of fast ice in the seasons 2003–2005 showed that, besides physical parameters, the coastline and islands in Kongsfjorden are crucial for the fast-ice extent. The protection by Lovénøyane preserves the fast ice and, thus, makes it suitable for monitoring studies into spring. The ice decay is strongly influenced by the



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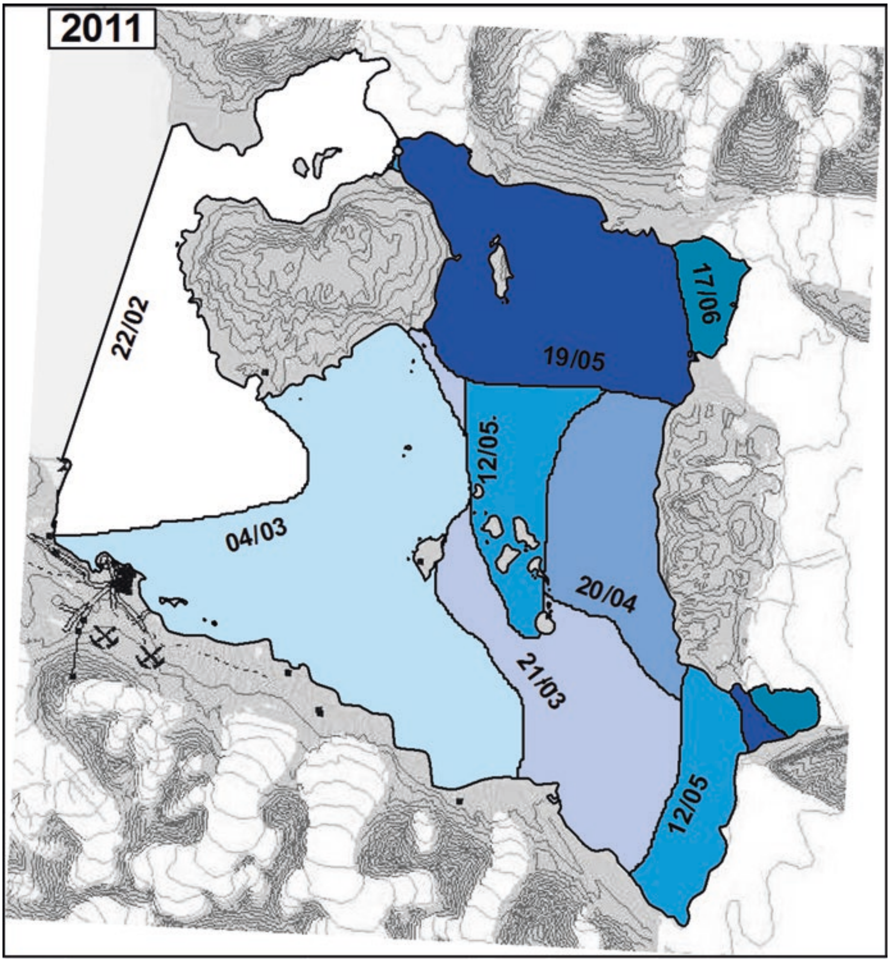
islands, and the plateau in the ice-extent vs time data series reflects this (Gerland and Renner 2007; their Fig. 4.4). These time series also show that ice once disconnected from shore, can stay as pack ice in the fjord for several weeks (e.g. in April 2005).

The duration and extent of fast ice in Kongfjorden are important for heat loss to the atmosphere and, thus for oceanographic processes with regard to formation of local fjord water, and, particularly winter cooled water with temperatures <−0.5 °C (Svendsen et al. 2002; Hop et al. 2006). With more Transformed Atlantic water being advected into Kongsfjorden, particularly during winter (Cottier et al. 2007, 2010), the entire fjord system has become warmer with less sea ice. The overriding effects seem to be oceanographic, with links to processes in Fram Strait (Hop et al. 2006; Walczowski et al. 2017; Tverberg et al., Chap. 3). Climate warming with



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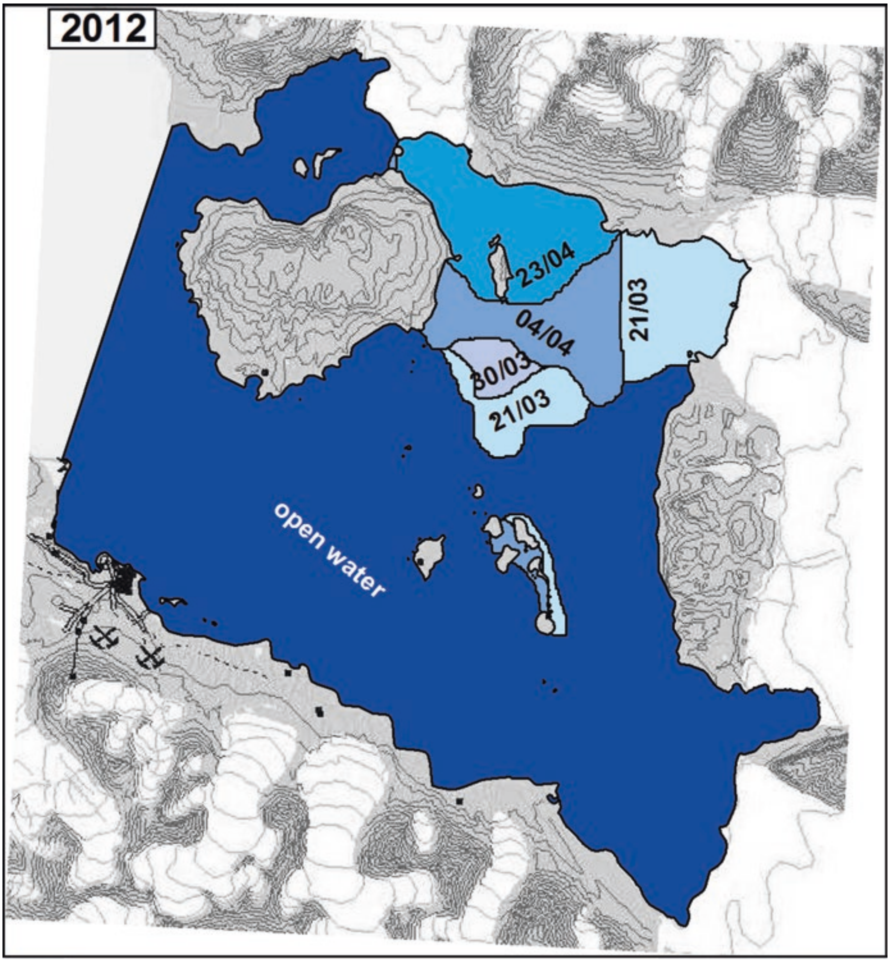
increased atmospheric temperatures, as evident from the temperature record for Ny-Ålesund, is the ultimate driver for changes in the marine environment.

Satellite observations have become a widely used tool for sea-ice studies, and researchers are increasingly able to utilize satellite-generated data, also in coastal areas. Muckenhuber et al. (2016) investigated sea-ice conditions for the period 2000–2014 in two fjords along the west coast of Spitsbergen (Isfjorden and Hornsund). Inter-annual variability of sea-ice cover in these two fjords corresponds well with our observations. For example, their estimates for Isfjorden (their Fig. 4.3) show two periods (2000–2005 and 2009–2011) with relatively high fast-ice coverage (40% and higher) and two periods (2006–2008 and 2012–2014) with relatively low fast-ice coverage (<30%). The authors also marked the years 2012 and 2014 as the years when the fast-ice season was significantly shorter and with maximum



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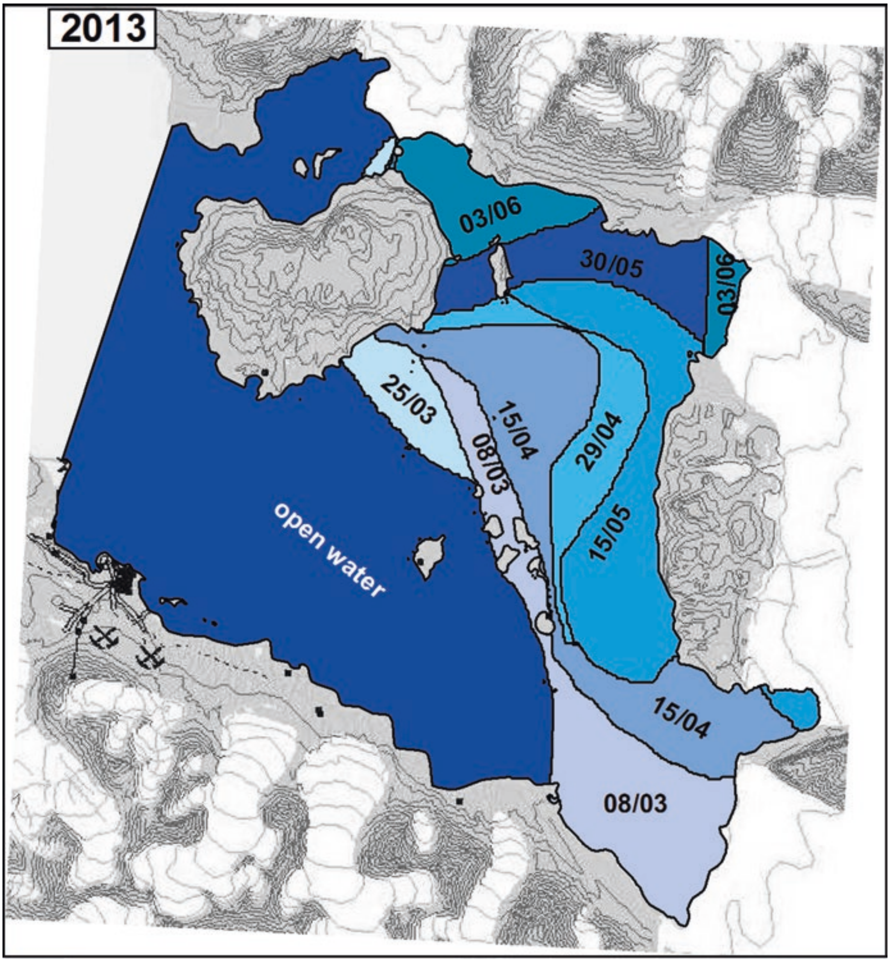
<20%. They concluded that fjord systems along west Spitsbergen changed from an Arctic state to a more Atlantic-water state after the winter 2005/2006. With regard to fast-ice coverage, we found the same periods (in terms of large and little ice coverage) as in Muckenhuber et al. (2016), except for the year 2006.

The winter 2005/2006 has been noted as a turning point toward a warming Arctic as a whole, and particularly in the fjords along West Spitsbergen (e.g. Comiso 2006; Cottier et al. 2007; Tverberg et al. 2007, Chap. 3; Muckenhuber et al. 2016). Based on satellite observations, Comiso (2006) reported on relatively high surface temperature and record-low ice extent during the winters of 2005/2006 in the peripheral seas, mostly in the eastern Arctic Basin. With regard to Kongsfjorden, Cottier et al. (2007) indicated that periods of sustained along-shelf winds during the winter 2005/2006 generated upwelling and cross-shelf exchange that caused extensive



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flooding of the coastal waters with warm Atlantic water from the West Spitsbergen Current. Based on analyses of oceanographic data from the period 1997–2007, Tverberg et al. (Chap. 3) suggested that the February 2006 event, with massive intrusion of Atlantic water to the fjord, was a tipping point for the Kongsfjorden environment. Then, the winter temperature of the West Spitsbergen Shelf remained elevated, interrupting the normal cycle of sea ice formation in the region.

Newer hydrographic observations (Cottier et al. 2007, 2010; Pavlov et al. 2013; Nilsen et al. 2016; Tverberg et al., Chap. 3) revealed the important role of wind-driven water masses that bring more Atlantic water to Kongsfjorden (and other West Spitsbergen fjords) than usual, contributing to less fast-ice formation. This, in combination with relatively mild winters, can be seen as main factors for changing fast-ice conditions in Kongsfjorden during the last 10 years.

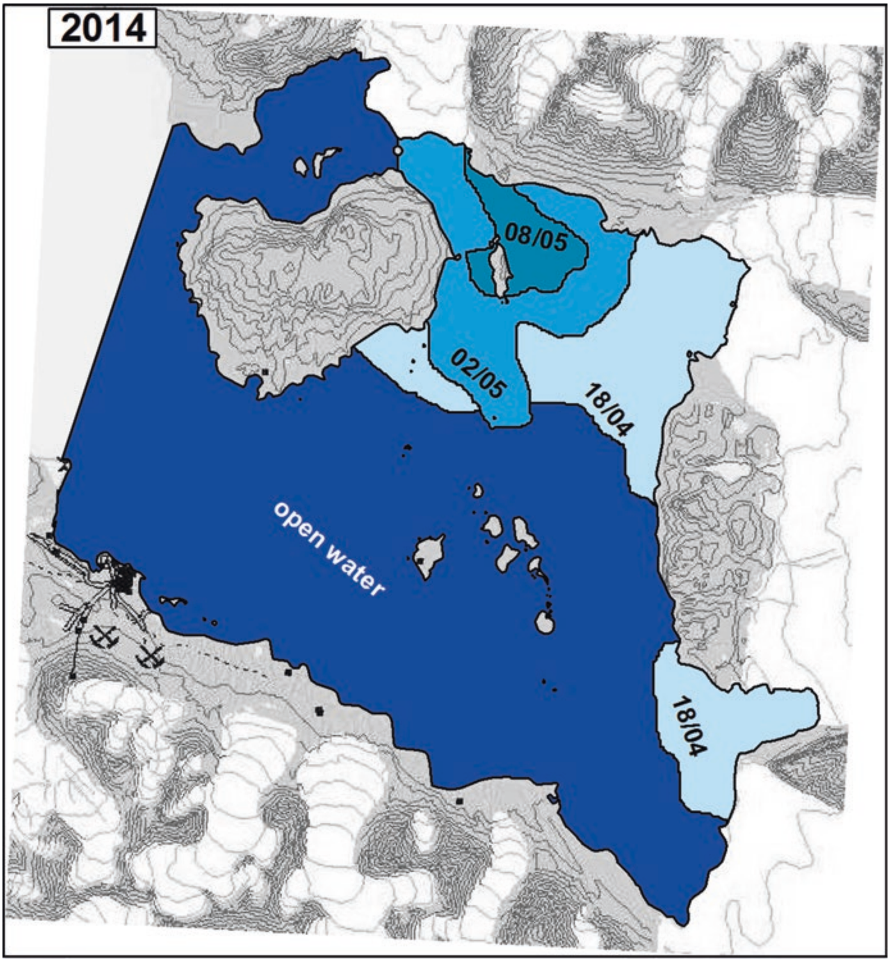

Fig. 4.3 (continued)

As detailed, ice conditions in the fjord are strongly linked to the atmospheric and hydrographic forcings, with periods of cold air and water necessary for ice formation. However, in addition to that, other factors play important roles: The timing of ice formation along with the given wind scenario influences how much snow accumulates on the fast ice. The snow cover again influences the growth of ice by (i) reducing ice growth speed, (ii) giving the potential of snow-to-ice formation (snow ice, superimposed ice), and (iii) being the base for melt ponds later in the season. Ice that starts to form later in the season might grow faster than ice that already has started to form, and less snow cover also enhances ice growth (Notz 2009). However the forcings appear too weak in recent years to create substantial fast-ice thickness, even with little snow cover.

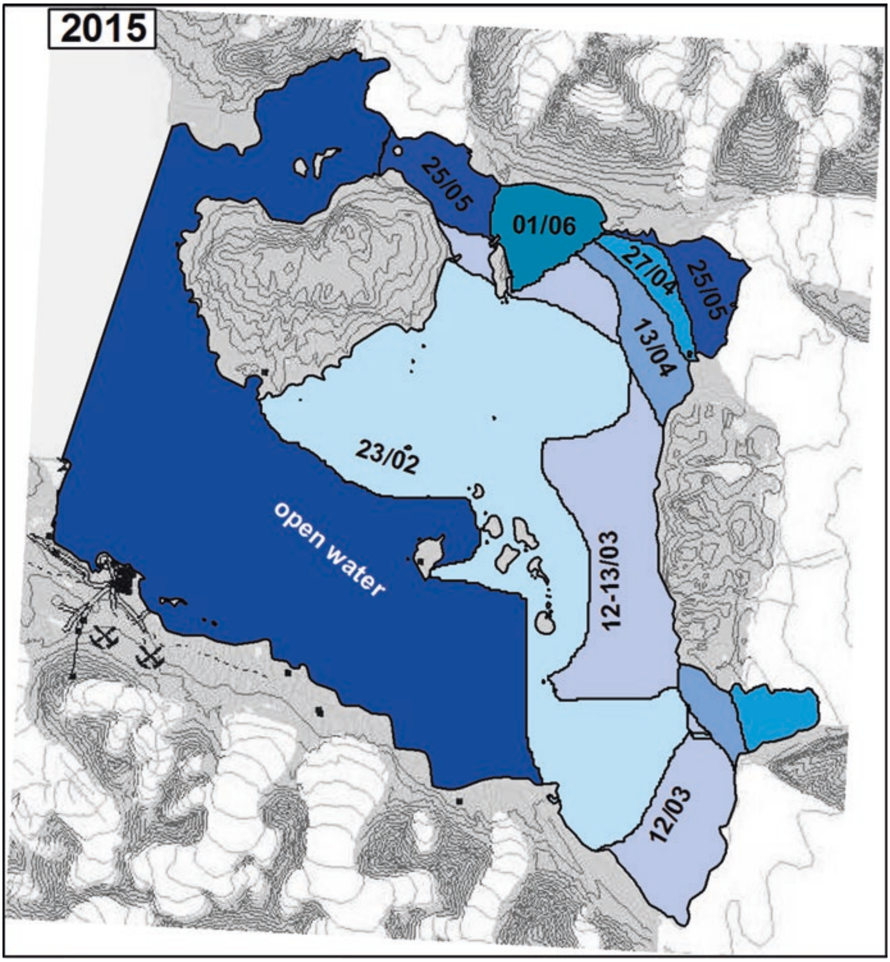

Fig. 4.3 (continued)

The relationship between snow and ice thickness shows that thick ice typically has more snow on it (Fig. 4.6). Thicker ice typically forms earlier in the season and persists longer, allowing more snow to accumulate. From observations (Gerland et al. 1999, 2004; Nicolaus et al. 2003) and modelling (Nicolaus et al. 2006; Wang et al. 2015), we know that snow ice and superimposed ice do contribute to ice and snow thickness evolution in Kongsfjorden. Based on these studies, we also know that air temperature and precipitation are critical factors for snow ice and superimposed ice formation, and that the total ice formation at the ice surface is more sensitive to precipitation than to air temperature. The precipitation on land in Ny-Ålesund has increased since during the period 1969–2013, particularly during the early snow season (October–February; López-Moreno et al. 2016). However, the number of days with rain also increased during this period, with 43% for the early snow season

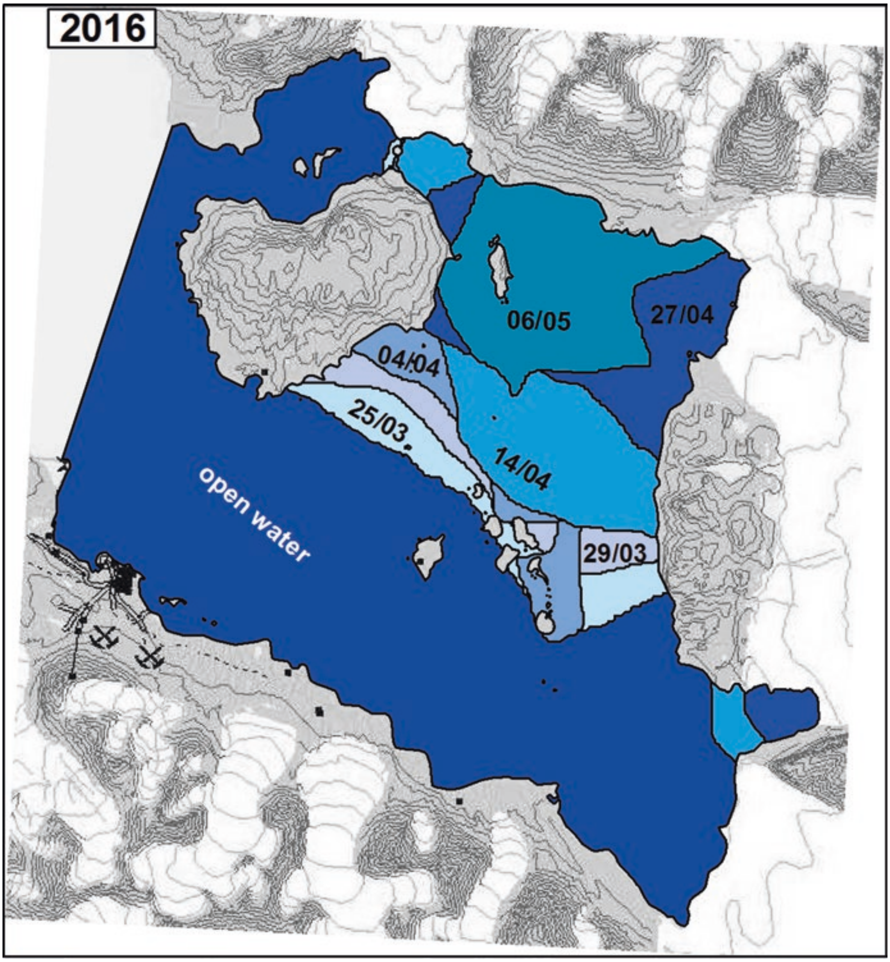

Fig. 4.3 (continued)

and 13% for the late snow season. This has caused a general decrease in snow pack thickness, water equivalent and duration as the climate warms.

Consistent monitoring of sea ice is challenging because of changing sea-ice conditions. Changes in glacier fronts present a challenge for ice monitoring in Kongsfjorden. For long-term monitoring, changing (retreating) glacier fronts lead to (i) change (increases) in the total surface area of the fjord, and (ii) new coastline and hydrographic conditions, which might be more or less suitable for fast-ice formation. Two examples for such changes are the opening of the area north of Blomstrandhalvøya in the early 1990s, when the glacier Blomstrandbreen retreated so that the former peninsula Blomstrandhalvøya became an island, opening also for water currents in the shallow passage (Svendsen et al. 2002; Burton et al. 2016). However, that change happened prior to the beginning of the monitoring presented

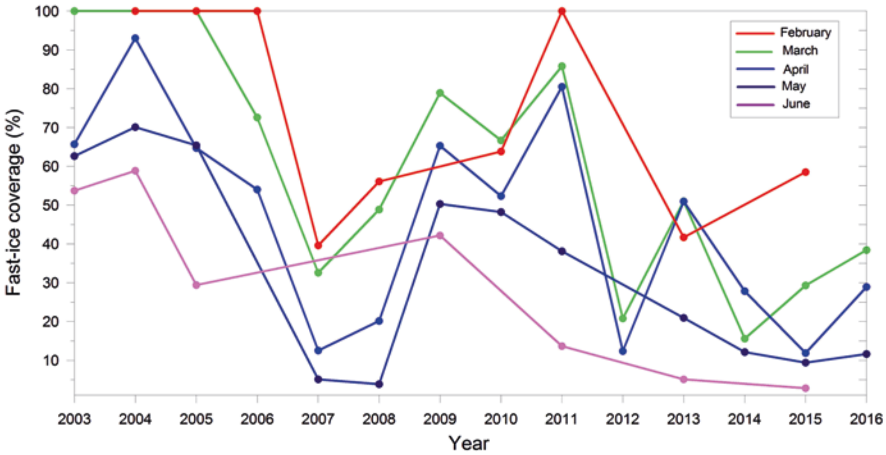

Fig. 4.4 Maximum fast-ice coverage (%) for each month from February to June in the period of 2003–2016

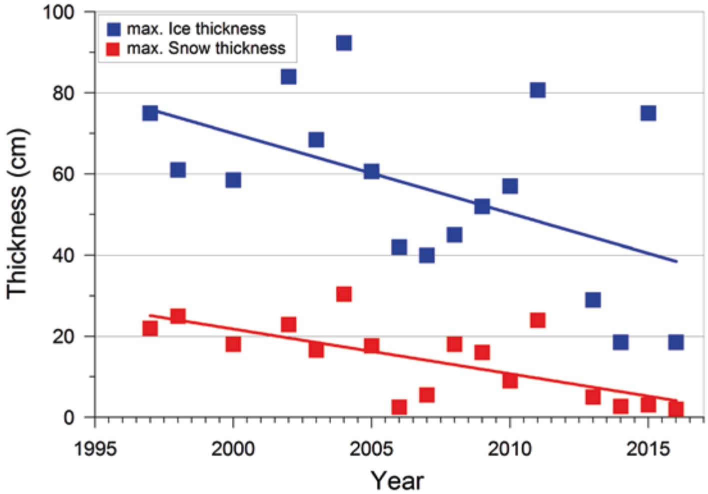

Fig. 4.5 Maximum seasonal sea-ice and snow thickness (cm) in inner Kongsfjorden 1997–2016. Lines show the linear trends: blue – ice-thickness changes (−24.7% per decade) and red – snow-thickness changes (−41.7% per decade). There were no *in situ* measurements in the years 1999 and 2001 because regular monitoring started first in 2003, and none in 2012 because of little ice. Observations from 1997, 1998, 2000 and 2002 were made in connection with research projects

here (Sund and Eiken 2010). A second example is the opening of the bay Raudvika north of Kronebreen in the 1970s (Liestøl 1988), with the main retreat after the 1990s (Urbanski et al. 2017). Well protected from swell and only with a limited opening to the rest of Kongsfjorden, the setting of this bay is suitable for fast-ice formation.

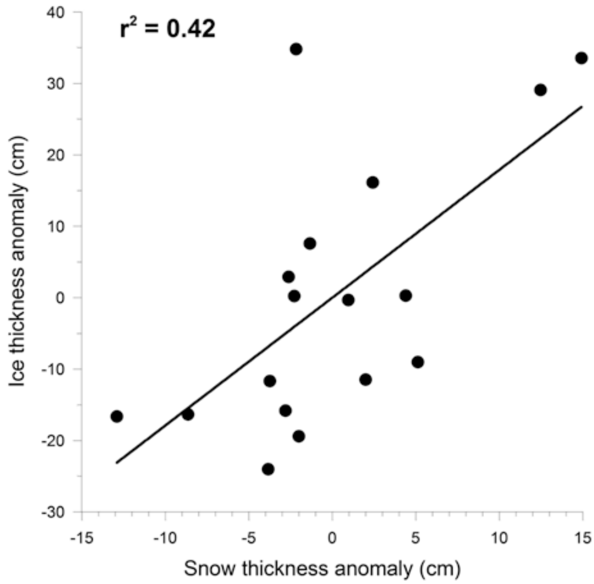

Fig. 4.6 Relationship between detrended maximum snow thickness (cm) and maximum ice thickness (cm) in Kongsfjorden, 1997–2016

Table 4.1 Monthly mean air temperature in Ny-Ålesund, Svalbard, for 2002–2016

Year	January	February	March	April	May	December
2002	-11.7	-12.4	-14.5	-7.1	**-3.9**	-6.9
2003	**-16.4**	-11.4	**-16.3**	-9.7	-3.1	**-17.0**
2004	-15.9	**-16.1**	-7.1	-3.2	-1.8	-7.7
2005	-7.4	-7.5	-14.4	-8.5	-1.8	**-3.9**
2006	**-3.3**	-10.8	-13.2	**-1.0**	0.2	-7.2
2007	-9.1	-8.8	-8.2	-11.4	-3.2	-8.8
2008	-7.7	-8.8	-14.3	-9.5	-2.4	-8.1
2009	-11.8	-10.5	-11.9	**-15.6**	-1.8	-5.2
2010	-8.0	-10.6	-13.9	-7.7	-0.3	-10.9
2011	-13.9	-10.7	-12.8	-5.3	-2.0	-6.9
2012	-3.6	-6.8	**-5.7**	-9.8	-2.1	-8.0
2013	-7.9	-10.8	-13.2	-9.2	-1.8	-8.7
2014	-4.7	**-2.7**	-9.2	-10.4	-3.4	-9.1
2015	-6.1	-13.8	-6.6	-5.8	-2.1	-7.0
2016	-4.8	-6.9	-7.5	-6.9	**1.0**	-6.7

The highest and lowest temperatures for each month are marked in red and blue, respectively

The long-term thickness observations presented here are to some extent biased by the fact that it was impossible to gather observations on identical locations throughout the entire observation period. This is due to that (i) several of the sites where monitoring fjord ice started have been ice free in recent years, and (ii) the inner fjord is often only accessible by small boat, not by snowmobile. When accessing the fast ice from a small boat, the distance from the ice edge that can be reached

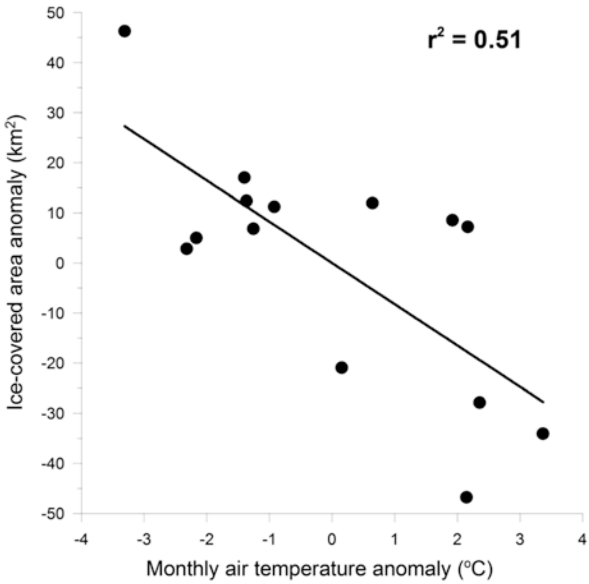

Fig. 4.7 Relationship between detrended monthly air temperature in Ny-Ålesund and sea-ice extent in Kongsfjorden during winter (January–March), 2003–2016

is rather limited. On the other hand, some locations where sea ice is present in recent years such as inner Raudvika and current glacier fronts did not exist as locations with sea ice in the early phase of the monitoring, since they were covered by glaciers.

Presence and properties of sea ice in polar waters are important for production and development of ice algal communities, but also for the later production by phytoplankton in the water column (Leu et al. 2015; Hegseth et al., Chap. 6). The presence of snow on top of sea ice affects both biomass and primary production rates of ice algae by blocking >90% of the light transmission through the ice (Grossi et al. 1987; Welch and Bergmann 1989; Ehn et al. 2011). Reduction of ice and snow thickness on fast ice in Kongsfjorden would likely increase production of ice algae during early spring, and may also shift the production season earlier in the year, as has been observed for other areas in the Arctic (Leu et al. 2015). However, the currently regularly observed thin snow cover will likely result in too much light and photoinhibition (Juhl and Krembs 2010; Campbell et al. 2015), and the concurrent reduction in sea ice in Kongsfjorden further limits the contribution of ice algae to the production in the fjord.

The pelagic spring bloom in Kongsfjorden typically starts in late April and lasts until mid-May, with total production in the range of 27–35 g C m^{-2}, as determined in 2002 by Hodal et al. (2012). At that time, the peak in production likely occurred in late April, in connection with ice break up. In later years (2002–2014), the bloom most often occurs in April, but may also occur later in May or early June (Hegseth et al., Chap. 6). The presence of sea ice, particularly with snow on it, affects the light climate experienced by phytoplankton during spring (Pavlov et al., Chap. 5). However, as pointed out by Hegseth and Tverberg (2013), the timing and magnitude of the spring bloom in Kongsfjorden seem to have little connection to sea ice or temperature during spring, but rather to winter convection, which brings up resting spores from the sediments needed for initiating the diatom bloom. Such blooms may also be intensified with the increased glacial run off in Kongsfjorden (Calleja et al. 2017). In warm years with late blooms (2007, 2008, 2014), the fjord had little sea ice and typically a pronounced thermocline. The late blooms were often dominated by *Phaeocystis pouchetii* (Hegseth and Tverberg 2013), with subsequent blooms of smaller phytoflagellates (Piwosz et al. 2009, 2015).

Sea ice also has influence on the benthos, because of reduction in radiation during early spring and also because of ice scouring in shallow regions. Hansneset, near Blomstrandhalvøya, experienced periods of sea ice before 2007, but generally not in 2007–2016, except for a short time in February 2011. Less ice scouring have caused an increase in abundance and biomass of macroalgae in shallow waters at this location, and the peak in biomass has moved upwards from a maximum at 5 m depth in 1996/98 to maximum at 2.5 m depth 15 years later (Hop et al. 2012; Bartsch et al. 2016). The depth extent of the macroalgal belt decreased by 2–5 m, which may be related to higher turbidity because of increased glacial run-off (Bartsch et al. 2016). Concurrently, the biomass and production of macrozoobenthos have increased in the upper sublittoral zone (Paar et al. 2016). However, the lack of ice and ice algae may have had a negative effect on soft-bottom benthos, which utilize ice algae in the vertical flux as seasonally concentrated food supply (McMahon et al. 2006; Kulinski et al. 2014). Changes in phytoplankton communities towards *Phaeocystis* and smaller flagellates, as seen in Kongsfjorden (Piwosz et al. 2009, 2015) typically leads to hither retention in the pelagic ecosystem and less export flux.

Some species at the upper trophic level have also been particularly influenced by changes in sea ice conditions in Kongsfjorden. Ringed seals (*Pusa hispida*) use snow that has accumulated on the lee side of glacial pieces in sea ice to make birth lairs (Lydersen et al. 2014). With less suitable ice habitat in Kongfjorden, the seal pups have become more vulnerable to predation by polar bears (*Ursus maritimus*), Arctic foxes (*Alopex lagopus*) and glaucous gulls (*Larus hyperboreus*), with resulting decline in reproductive success (Lydersen et al. 2014). During the years of little ice on fjords on the coast of West Spitsbergen, their reproduction was low to non-existent (Kovacs and Lydersen 2008).

Some of the seabird species in the Kongsfjorden area may have benefitted from less sea ice. For surface feeding seabirds, such as the black-legged kittiwake (*Rissa tridactyla*), less sea ice during spring results in larger foraging areas along the coast. With increased Atlantic influence, more prey species have become available for feeding and the population has increased in the years after 2003 (Vihtakari et al. 2018). Common eiders (*Somateria mollisima*) breed on the islands in inner Kongsfjorden, such as Lovénøyane. Less sea ice during spring has caused less access to these islands by one of their main predators, the Arctic fox, which has resulted in higher number of breeding birds (Hanssen et al. 2013).

4.6 Conclusions

Fast ice, and ice and snow thickness in Kongsfjorden have been monitored regularly for 14 years. This study is ongoing, and a major aim is to identify and quantify connections between the fast-ice evolution in Kongsfjorden and climate variability during the last decade. In particular, atmosphere and ocean-related drivers need to be reviewed. The oceanography is typically monitored during regular surveys in Kongsfjorden conducted by NPI and Institute of Oceanology (IOPAN) during summer and by UiT/UNIS during winter, but more detailed CTD-measurements in connection with fast ice in Kongsfjorden are clearly needed.

Further sea-ice monitoring should:

- Quantify the fast-ice mass balance in Kongsfjorden
- Generate a baseline for typical fast-ice evolution scenarios in Kongsfjorden
- Make comparisons of fast-ice coverage in Kongsfjorden and other Svalbard fjords
- Identify possible links between fast-ice mass-balance data and climate index parameters
- Provide background data for interdisciplinary studies

Observations of changes in fast-ice properties, especially when combined with similar observations from other locations, may provide a relatively inexpensive way to monitor changes in the oceans and the atmosphere. Sea-ice monitoring in Kongsfjorden is not only used for climate change research, it also contributes to past, ongoing and future process studies in many disciplines conducted by the international research bases at Ny-Ålesund. In the future, *in situ* measurements will be better complemented by satellite observations. New technology, such as remote sensing with higher resolution and more frequent data recording (e.g. with the new ESA Sentinel satellites), gives possibilities to develop more precise methods and tools to describe the sea-ice regime in Kongsfjorden.

Changes in sea−ice and hydrographic conditions observed in Kongsfjorden from 2003–2016 have altered the production regime from ice algae and early diatom blooms, towards later blooms of flagellates. The reduction in sea ice extent, ice thickness and duration of ice cover have reduced the suitable habitat for ice algae, and therefore their contribution to the total primary production in Kongsfjorden. The production regime for phytoplankton has also changed, as pointed out in Hegseth et al. (Chap. 6), although this is probably more related to changes in advection of water masses and increased run-off from glaciers. The benthic production on hard-bottom have increased in the shallow regions because of less ice scouring, but may have decreased for soft-bottom communities because of less vertical flux of ice algae and large diatoms. For upper trophic levels, reductions in fast ice have been negative for species that rely on sea ice for reproduction, particularly for ringed seals. On the other hand, less sea ice during spring has been beneficial for species that forage in open water, such as the black-legged kittiwake, and eiders breeding on islands in the inner part of Kongsfjorden. Thus, changes in the lower part of the food web have involved a combination of factors (ocean warming, advection of water masses, sea ice reduction, glacial run-off, changes in light regime), whereas effects of declining sea ice on the upper part of the food web have targeted particular species, negatively or positively.

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