Long-term monitoring of landfast sea ice extent and thickness in Kongsfjorden, and related applications (FastIce)

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1. Introduction

Landfast sea ice covers the inner parts of Kongsfjorden, Svalbard, for a limited time in winter and spring months, being an important feature for the physical and biological fjord systems (Figure 1). Systematic fast-ice monitoring for Kongsfjorden, as a part of a long-term project at the Norwegian Polar Institute (NPI) was started in 2003, with some more sporadic observations from 1997 to 2002. It includes the ice extent mapping and in situ measurements of ice and snow thickness, and freeboard at several sites in the fjord. The permanent presence of NPI personnel in Ny-Ålesund Research Station enables regular in situ fast-ice thickness measurements as long as the fast ice is accessible. Further, daily visits to the observatory on the mountain Zeppelinfjellet close to Ny-Ålesund, allow regular ice extent observations (weather, visibility, and daylight permitting). Data collected within this standardized monitoring programme have contributed to a number of studies. Monitoring of the sea-ice conditions in Kongsfjorden can be used to demonstrate and investigate phenomena related to climate change in the Arctic.

Figure 1: Landfast sea ice in Kongsfjorden in spring 2009, with an iceberg in some distance. (Photo: S. Gerland)

2. State of fast-ice monitoring for the period 2003-2019

2.1 Method

Conception and methodology of the systematic fast-ice monitoring in Kongsfjorden are described in Gerland and Hall (2006), Gerland and Renner (2007) and Pavlova et al. (2019). The fast-ice extent observations are based on visual observations for days with sufficient daylight, and, accordingly, no data are available for days when there is limited visibility (low clouds, fog and darkness). The maps are drawn by hand visually assessing the ice edge, and photographs are taken from Zeppelinfjellet. In maps and from photographs, we classify the ice as "fast ice" and "drift ice". Ice thickness and freeboard are measured conventionally from drill holes on up to five sites in the inner fjord, using a 2" auger and a Kovacs thickness-gauge tape measure or a measurement stick with a notch. The snow thickness is measured with a metal stake.

2.2 Fast-ice extent

The fast-ice coverage reached its maximum (120 km^2) within the defined observation area in the years 2003-2006 and 2011 (Pavlova et al. 2019, their Figure 3). The period after 2006 was characterised by relatively little sea-ice cover and shorter ice cover season, except 2011. The lowest ice extent (21%) was observed in 2012. The time series of maximum fast-ice coverage for each of five months (February-June) in the period 2003-2019 shows alternating periods of extensive and little ice cover (Figure 2). Maximum fast-ice coverage values (100% of the surveyed area in the fjord) in February were reached in the years 2004-2006 and 2011. For 2003, no ice-cover information is available prior to March, and in 2004 the entire observation area was ice-covered with fast ice in mid-January (not shown) and also registered in February. 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% of ice-covered area) were observed in 2004 and 2011, respectively. In the two other months (May-June), in the years when fast ice was observed then, the maximum fast-ice coverage was below 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 between February/March and April. During the periods 2007-2008 and 2012-2019, fast ice covered less than 50% of the study area, except for February 2008 and 2015, and for March 2018 and 2019. Based on available visual observations, late ice growth, low coverage and short seasons of fast ice were observed in the years 2012, 2014, 2016 and 2017. Despite the lowest February ice coverage (during the monitoring period) observed in 2018 (2.5%), ice extent in March 2018 was relatively high (66.7%). Finally, also the year 2019 can be counted among years with a rather short sea ice season, but with relatively high per cent of fast-ice coverage in February

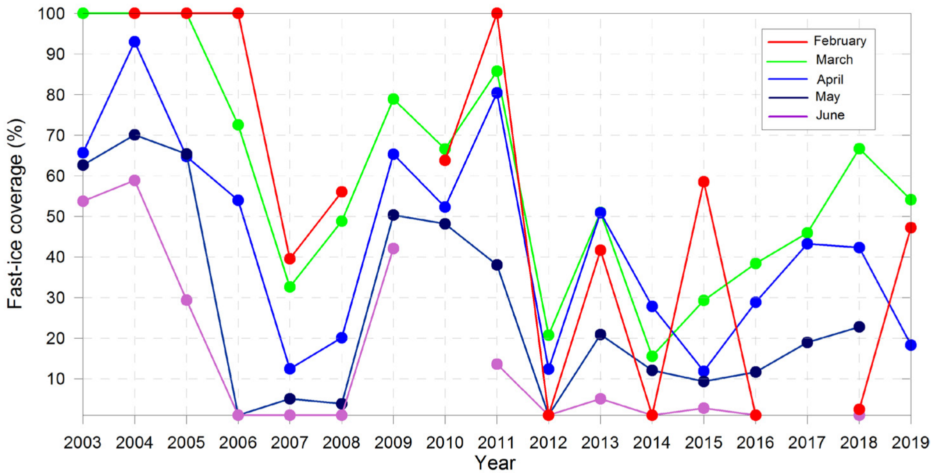

Figure 2: Maximum fast-ice coverage for each month from February to June (2003-2019). Gaps in the lines are related to years/months where no data are available.

and March (near 50%). Based on conditions from 2003-2019, 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; and ii) most years after 2006 had low ice extent and short seasons of fast ice.

Over the last 30 years, the coastline has changed due to glacier retreat, and therefore the observation area has increased. This does not only increase the available area for ice formation, it also alters conditions for ice formation through creation of new areas/bays protected from swell and waves.

2.3 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 (Pavlova et al. 2019). Before 2006 the ice was usually at least 0.6 m thick. In recent years until 2016, except for 2011, values decreased to around 0.2 m. The linear trend of that change for the period 1997-2016 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 in the same period from around 0.2 m to < 0.05 m, exhibiting an even larger negative trend in relative values with -41.7% per decade.

After 2016, in most areas ice thickness was still at low levels, with the exception of the wave-protected area of Raudvika (a bay in inner Kongsfjorden, which is increasing in size due to glacier retreat), where sea ice well over 0.2 m thick was observed.

The snow cover on sea ice slows down ice growth (relative to sea ice without a snow cover), but it also can, under specific conditions, contribute to the sea ice growth. From observations (Gerland et al. 1999, 2004; Nicolaus et al. 2003) and modelling (Nicolaus et al. 2006; Wang et al. 2015), it is known that snow ice and superimposed ice do contribute to ice and snow thickness evolution in Kongsfjorden. Air temperature and precipitation are critical factors for snow ice and superimposed ice formation, and the total ice formation at the ice surface are more sensitive to precipitation than to air temperature (Wang et al. 2015).

2.4 Related applications

The sea ice monitoring in Kongsfjorden represents additional value beyond what it contributes to climate research. A larger number of process- and validation studies with links to the role of sea ice in the fjord has been conducted in Kongsfjorden since the late 1990s. Here, we discuss a few examples of such studies conducted in recent years. Advantages of using the landfast sea ice in the fjord for a number of applications are: (i) the fact that the fast ice is not mobile, giving the opportunity to install measurement equipment that can relative easy be retrieved later, and it helps for connecting satellite imagery to features on the ice observed with a small time difference; and (ii) the fact that most of the fast ice properties are largely homogeneous in horizontal dimensions, which means it can serve as a 1-D case for testing process models, and findings from one site can be extended within some (limited) area around the observation site.

Sea ice in Kongsfjorden was used for two studies validating SAR (Synthetic Aperture Radar) satellite remote sensing products (Negrel et al. 2018, Johansson et al. in press). It could be demonstrated, that under certain circumstances, the edge of the fast ice can be reasonably well mapped using SAR products, however, limitations of this method were visible, for example, when the sea ice is less than 0.1 m thick, SAR methods were not able to distinguish sea ice from open water. This is important when further developing satellite methods in order to aid or even replace direct observations.

Another validation study focused on the remote sensing application of Global Navigation Satellite System (GNSS). Such GNSS, like the US-operated Global Positioning System (GPS), provide signals with global coverage initially meant for navigation. The study conducted at Kongsfjorden examines the reflected GNSS signals for remote sensing of the sea surface and the adjacent glaciers (Peraza et al. 2017). Under certain conditions, sea ice properties, e.g. its concentration, can be derived from the reflected signals (Semmling et al. 2019). A challenge for the setup at Kongsfjorden is that in recent years, the fjord area in immediate vicinity of Ny-Ålesund was usually free of ice also in winter.

Interesting scientific questions, when looking at environmental changes, address the couplings (e.g. energy fluxes) between atmosphere, sea ice and ocean, including fjords. Ultimately these processes control how much and which type of sea ice is present in a region. In a recent study (Dahlke et al. unpublished data) the coupling of atmospheric properties and sea ice extent is investigated, with a focus on the Svalbard region. Comparing information on surface air temperature (SAT) and sea ice extent (SIE) in Svalbard fjord systems led to the conclusion that, on time scales of a few months, changes in SAT affect SIE more than the other way around. This is an important finding for improving the understanding of the Arctic system, and how the system is changing, from local to larger scales.

2.5 Conclusions

Fast ice and ice and snow thickness in Kongsfjorden have been monitored regularly since 2003. This study is ongoing, and a major aim is to identify and quantify connections between the fast-ice evolution in Kongsfjorden and climate variability, in particular atmosphere and ocean related drivers. Consistent monitoring of sea ice is challenging because of changing observation area settings. Changes in glacier fronts present a challenge for fast-ice monitoring in Kongsfjorden. For long-term monitoring, changing (retreating) glacier fronts lead to (i) change (increase) in the total surface area of the fjord, and (ii) new coastline and hydrographic conditions, which might be both less and more favourable for fast-ice formation.

Sea-ice monitoring in Kongsfjorden is not only used for climate change research, it also contributes to past, ongoing and future process and validation studies in many disciplines conducted at the Ny-Ålesund Research Station. For the future, *in situ* and visual measurements are planned to be regularly complemented or even (partly) substituted by satellite observations. Satellite remote sensing with a higher resolution and more frequent coverage (e.g. with the new ESA Sentinel satellites) promotes development of more accurate methods and tools to describe the sea-ice regime in Kongsfjorden.

3 Unanswered questions

Current monitoring is limited in temporal and spatial resolution. Local information on atmospheric and oceanic forcing is also limited. Further changes of the fast-ice evolution might lead to new and not yet observed scenarios, where new processes and feedbacks could play a role.

The sea ice evolution in Kongsfjorden has been modelled with a 1-D process model (Wang et al. 2015), but not yet with a coupled regional model. Such work could improve the understanding of the observed changes.

4 Recommendation for future

The monitoring presented here started in 2003 and has resulted in a much better understanding of the seasonal evolution of landfast sea ice in Kongsfjorden, and how it varies and changes over time. Results have also contributed to several (partially interdisciplinary) process studies. The value of the time series is increasing the longer the series becomes. We recommend to continue the monitoring as a robust and affordable initiative. While keeping consistency in the methods, it can also help and improve the monitoring programme to introduce modern and autonomous technology. For example, experiments with automatic time-laps cameras have successfully been implemented. We further recommend to continue developing tools based on optical and radar satellite remote sensing for supporting the established monitoring methods. Finally, further development of a sea ice component in a coupled regional model could improve the understanding of changes and variability observed, and in return the observations may help to improve modelling of sea ice.

5 Data availability

Data from the described monitoring initiative are planned to be made available on data.npolar.no.

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