Gerland, S., Haas, C., Nicolaus, M. & Winther, J-G. 2004. Appeared in: C. Wiencke (ed.) 2004. The coastal ecosystem of Kongsfjorden, Svalbard. *Reports on Polar and Marine Research*, No. 492, Alfred Wegener Institute for Polar & Marine Research, Germany, pp. 26-34.

Seasonal development of structure and optical surface properties of fast ice in Kongsfjorden, Svalbard

S. Gerland[1], C. Haas[2], M. Nicolaus[2] & J-G. Winther[1]

1: Norwegian Polar Institute, The Polar Environmental Centre, 9296 Tromsø, Norway
2: Alfred Wegener Institute for Polar and Marine Research, P.O. Box 120161, 27515 Bremerhaven, Germany

Introduction

This paper provides a brief overview on physical parameters and surface processes of Arctic fast ice throughout spring in Kongsfjorden, Svalbard, studied in the years 1997, 1998, 2002, and 2003. Kongsfjorden is an Arctic fjord on the western coast of Spitsbergen with seasonal fast ice in its inner part (Svendsen *et al.* 2002). The timing of its fast ice formation, snow and ice surface changes and ice disappearance has high influence on the local heat budget of the atmosphere-ice-ocean system, the salt budget in the fjord and the ecosystem. Fast ice formation and decay is closely related to the oceanic boundary conditions such as influence from the West Spitsbergen Current. Due to relatively warm water of Atlantic origin, fast ice forms late (usually not before December) compared with other Arctic locations, e.g., in the Canadian Arctic (e.g., Brown and Cote 1992). Kongsfjorden is usually free of fast ice from July to December. Despite Kongsfjorden fast ice differs in several aspects from other thermodynamically grown first-year ice in the Arctic and Antarctic, the fjord is well suitable for studies of small scale processes that affect sea ice and snow formation and decay.

Before 1997, information on the ice extent in Kongsfjorden is mainly availably in the form of data collected in the context of biological studies (Mehlum 1991; Lydersen and Gjertz 1986). Only recently, several sea-ice glaciological research projects were conducted by the Norwegian Polar Institute and the Alfred Wegener Institute, dealing with the physical properties of ice and snow, and with the development and decay of fast ice in the inner part of Kongsfjorden (Fig. 1). For the energy balance, the snow cover and upper ice layers are most important, because they affect albedo and solar radiation transmissivity most. In 1997, 1998, 2002, and 2003, detailed studies of optical surface properties like spectral reflectance and albedo, were performed as well as investigations of melt processes and superimposed ice formation (Gerland *et al.* 1999; Winther *et al.* 2001, 2004; Nicolaus *et al.* 2003; Hamre *et al.* accepted). The maximum mean total ice thickness in Kongsfjorden was observed to be ca. 0.9 m or less in all years. This includes a snow layer on top with maximum mean thickness of 0.23 m (Gerland *et al.* 1999; Nicolaus *et al.* 2003).

Here, the main results of these studies are summarized. We focus on the development of ice concentration in Kongsfjorden, snow and ice thickness, texture of snow and sea ice, salinity and temperature, and spectral surface reflectance and albedo during the transition from late winter to summer conditions.

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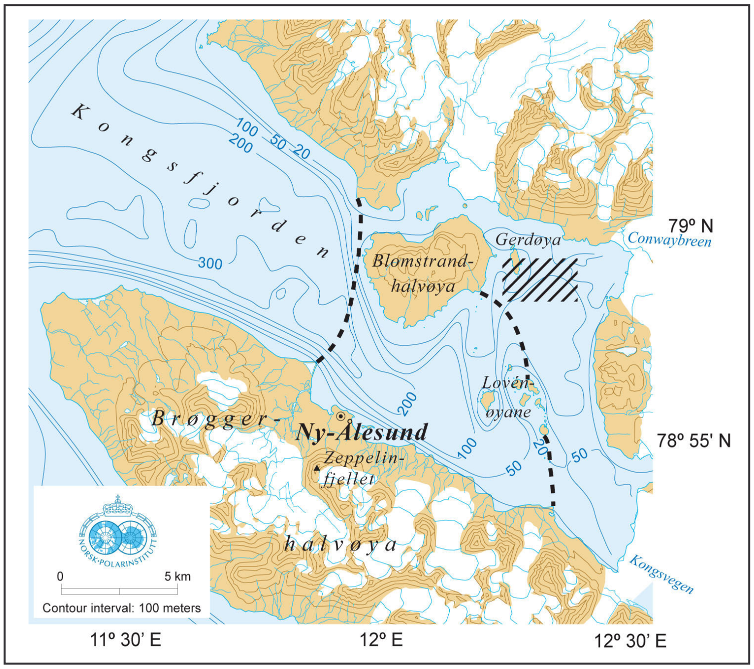
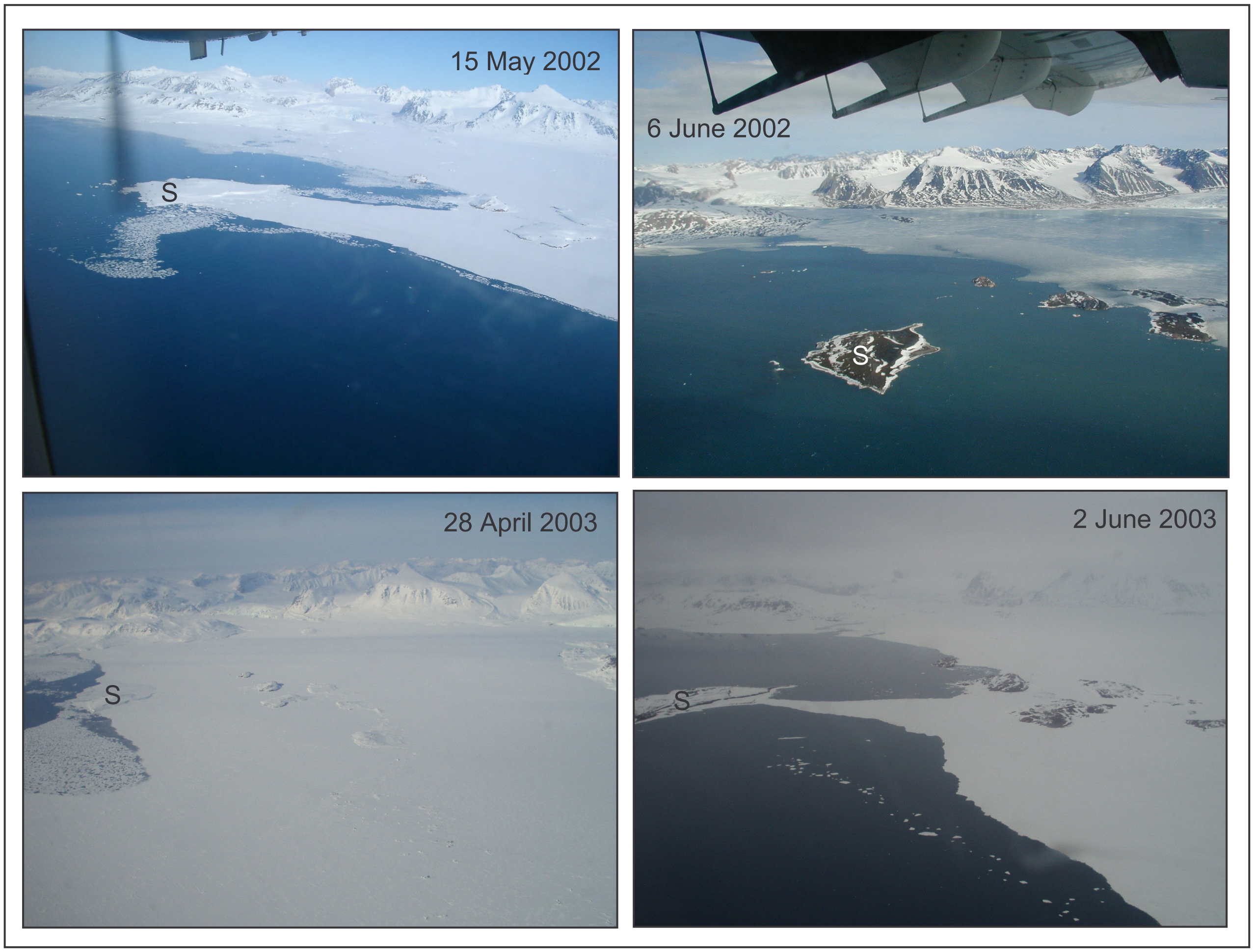


Fig. 1 (left): Map of Kongsfjorden with the research area indicated (marked rectangular box in the inner northern part of the fjord). Dotted lines show ice edge positions for years with more (left) or less fast ice (right) in the fjord. See further explanation in the text.

Fig. 2 (below): Aerial photographs (northward view) of the inner part of Kongsfjorden at different times of the year, before (left) and after (right) melt onset (see dates in the photographs). For orientation, the island "Storholmen" (the westernmost island of the "Lovénøyane") is marked with an "S". (photos: C. Haas, M. Nicolaus, 2002 & S. Gerland, 2003).



Furthermore, studies will be presented regarding formation of snow ice in winter and early spring, and superimposed ice after melt onset or during warm episodes in early spring.

Freeze up, maximum ice extent

No work has been published yet describing the onset of fast ice formation in Kongsfjorden. However, observations and knowledge of the hydrographic background conditions (Svendsen *et al.* 2002) give reason to assume that initial fast ice forms first in the inner, northern part of Kongsfjorden between December and early February. There, the water is shallower than in the transition zone and outer parts of the fjord, hence it is less influenced by Atlantic water, and it is protected from swell and waves. The islands Gerdøya, Lovénøyane and some smaller nameless islands form fixing points for fast ice formation. Ice core analysis from a core from the inner part of the fjord show granular ice layers in the upper part, and vertical columnar ice with very long crystals underneath, formed under calm conditions (Gerland *et al.* 1999). Typical thicknesses for the granular ice layer are 0.10-0.12 m and for the columnar ice 0.50-0.60 m. In addition to the fast ice, sea ice from other areas may be advected into Kongsfjorden. This “imported” sea ice may originate from drifting, broken-off fast ice from the nearby Krossfjorden, or first-year and multi-year ice from the area off the west coast of Spitsbergen, for example originating from the Arctic Ocean or the Barents Sea, drifting eventually with the West Spitsbergen Current northwards to Kongsfjorden. Throughout spring it is regularly observed that parts of the fast ice in Kongsfjorden break off and drift in and out the fjord, sometimes freezing again onto the original fast ice edge, forming an ice cover with a rough surface. Another contribution to ice types in Kongsfjorden is icebergs from the glaciers terminating in the fjord (e.g. Kongsvegen, Conwaybreen, see Fig. 1). The quantification of the areal fraction of such “imported” ice types is difficult. Icebergs are found embedded in the fast ice usually in shallow areas, often grounded, in the inner part of the fjord. Then, the areal fraction of those icebergs is small. In summer, when the fast ice disappeared, they are often the only forms of ice in the fjord. Sea ice from Krossfjorden may drift relatively easy into Kongsfjorden, because Krossfjorden is close to Kongsfjorden. No own observations of multi-year sea ice in Kongsfjorden exist, but there exists certainly the possibility that multi-year ice can be imported to Kongsfjorden.

The position of the ice edge, portions of drifting ice and icebergs varies significantly from year to year. In aerial photography from 2002 and 2003 (Fig. 2), it can be seen that the Lovénøyane play an important role in protecting the ice in the inner zone. This is also obvious from earlier observations (Lydersen and Gjertz 1986; Mehlum 1991). In a LANDSAT TM satellite image taken in early May 1998 (Svendsen *et al.* 2002), a situation with relatively high amounts of fast ice in Kongsfjorden was observed in spring, when also *in situ* observations were obtained (Gerland *et al.* 1999). Typical fast ice extent towards the mouth of the fjord for years with more or less fast ice is indicated in Figure 1. Occasionally, fast ice covers the entire fjord over shorter periods, joining the fast ice covers of Krossfjorden in the north and Forlandsundet in the south.

During winter and spring, before the onset of melt, there are also other ice formation processes than just congelation freezing. These are snow ice formation (Gerland *et al.* 1999), and occasionally early superimposed ice formation. Snow ice forms as a result of seawater flooding of the snow/ice-interface in the case of negative ice freeboard, and subsequent freezing of the seawater-saturated snow layer. Early superimposed ice forms during episodic warm spells, when surface snow metamorphoses or melts, and the melt water percolates downwards through the snow pack where it refreezes on colder layers, mainly ice lenses, or the snow/ice-interface. Rainfall during episodic spells in winter or early spring can also contribute to superimposed ice formation. The setting of Svalbard, where warm spells lead sometimes in winter to temperatures around or even above 0°C, enables for early superimposed ice formation. Corresponding conditions might be existent in Arctic/Sub-Arctic areas such as parts of the Barents Sea, but not in the major parts of the Arctic Ocean and more eastern Siberian shelf seas. A recent study with sampling of ice in inner Kongsfjorden in April 2003 (Gerland *et al.* unpubl.) revealed early formed snow ice and superimposed ice with a bulk layer thickness of 0.16 m. Superimposed ice and snow ice are general ice types both in the Arctic, Antarctic (e.g., Eicken *et al.* 1994), as well as in the Baltic Sea (e.g., Granskog *et al.* 2003). They increase the overall sea ice thickness significantly, and can therefore prolong the presence of the ice cover in summer, contributing to the total sea ice mass budget and mean surface albedo. Also on a small scale, they affect the physical and optical properties of snow and sea ice. Superimposed ice formation has been observed to happen in Kongsfjorden regularly around the time of the onset of melt (Gerland *et al.* 1999, see below).

Ice properties at the end of winter

In May, the fast ice reaches its maximum thickness of about 0.7 m with a snow layer of ca. 0.2 m thickness on top (e.g. Gerland *et al.* 1999). However, ice and snow thickness vary both locally and interannually. In addition to thickness determination by drilling, indirect measurements were applied using electromagnetic induction sounding in 1997 (Gerland *et al.* 1999), and 2003 (Fig. 3), when the total ice thickness was about 0.7 m.

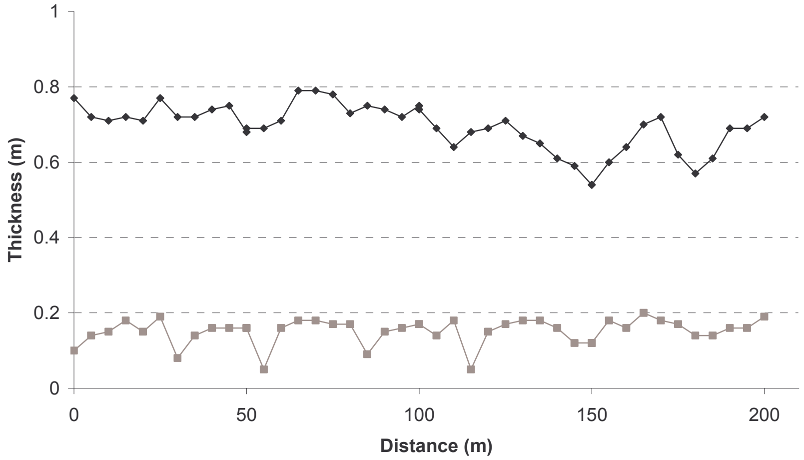


Fig. 3: Total ice and snow thickness along a 200-m profile south of Gerdøya, measured by means of electromagnetic profiling (total snow and ice thickness, upper curve) and snow-stake sounding (lower curve) at the end of April 2003. Although the ice appears level and undisturbed, it exhibits significant thickness variations over short distances.

As long as mean air temperatures stay below the freezing point of sea water, ice temperature vs. depth profiles exhibit negative gradients with near air temperatures at the surface and near seawater freezing temperatures at the bottom of the ice (Gerland *et al.* 1999). Due to the snow layer, most of the diurnal temperature variations do not reach deep into the ice in May, as monitoring revealed (Nicolaus *et al.* 2003, Gerland, unpubl. data). With no or only little formation of snow ice or superimposed ice layers, the salinity profiles resemble typical C-shape profiles with raised values at the top and bottom (Fig. 4a, March measurements, see also Gerland *et al.* 1999; Nicolaus *et al.* 2003), as known from other investigations of first year sea ice (Eicken 1992). Towards the onset of melt, salinity is decreasing in the upper parts of the sea ice, until the gradient eventually changes direction and salinities increase with depth (Fig. 4a, May and June measurements, see also Gerland *et al.* 1999; Nicolaus *et al.* 2003). However, in 2003, with extensive early superimposed ice and snow ice formation, salinity profiles with stronger variations in the surface layers were observed. Surface snow undergoes metamorphosis throughout spring with eventual grain growth, rounding and increased transparency for solar radiation. The change in snow crystal size, grain shape, liquid water content and thickness affects the surface albedo, resulting in a continuous decrease of albedo for 2002 (days 141-149) and 2003 (entire observation period, Fig. 5a). Fresh snowfall may lead to intermediate short-term increases of albedo.

Textural analyses reveal a crystal stratigraphy typical for fast ice. An ice core obtained in inner Kongsfjorden on 18 May 1997, consisted of a mixed layer of granular ice and ice with small columns in the uppermost 0.11 m, underlain by a transition zone of 20 mm thickness with larger ice columns (Gerland *et al.* 1999). Below, columnar ice with large vertical crystals (Fig. 4b) extended down to the bottom of the ice. There, the skeletal layer was inhabited by large amounts of ice algae, giving the lowermost 40 mm of the ice a brownish appearance. Analyses of melted samples from spring 1998 revealed that diatoms, such as *Nitzschia* spp., dominate (Hop *et al.* 2002).

Melt processes and ice decay

In the first weeks after melt-onset, the total ice thickness was observed to change only little (Gerland *et al.* 1999). However, superimposed ice formation at the surface and melting at the ice bottom obviously progress simultaneously, resulting in a principle change in the composition of the ice. Further, melting processes alter the textural and mechanical properties of the ice substantially because porosity increases by internal melting. This reduces the mechanical stability (fracture toughness) of the ice. The increased sea ice porosity was reported by Gerland *et al.* (1999) in a thin section of a core taken on 18 June 1997 (Fig. 4c). Sea water and brine-filled pore space in sea ice functions also as a habitat for ice algae.

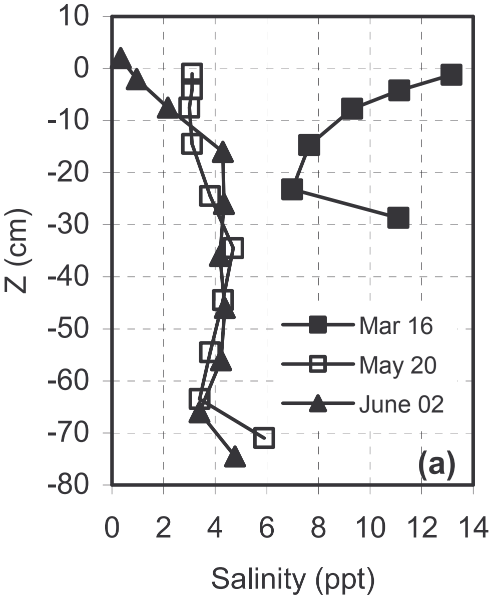
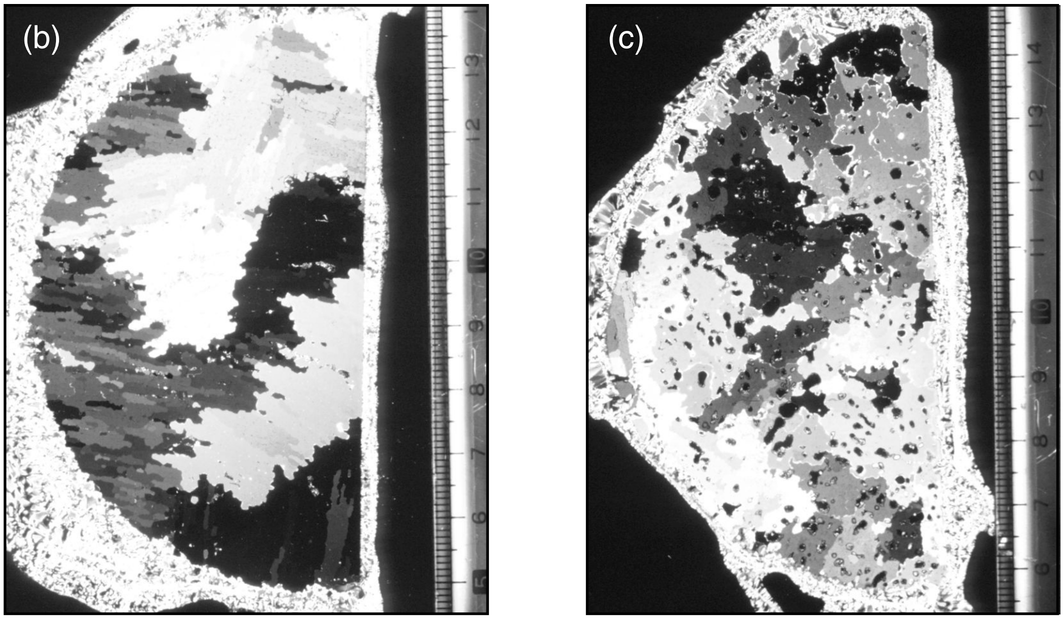


Fig. 4: (**a**, above) Typical ice salinity profiles obtained in 2002 at different stages of ice development. The May and June profiles show the complicated stratigraphy due to the presence of snow ice and superimposed ice (from Nicolaus *et al.* 2003). (**b**, below left) Horizontal thin section showing large crystals of columnar ice between crossed polarizers from 18 May 1997 at Dyrevika, and (**c**, below right), a corresponding thin section from 18 June 1997 from a core obtained near Gerdøya (from Gerland *et al.* 1999). Here, the enhanced porosity after the onset of melt is apparent. (b & c from Gerland *et al.* 1999).



Ice core samples, obtained in 1998 (Gerland *et al.* 1999) and 2002 (Nicolaus *et al.* 2003), show superimposed ice at the surface formed after the onset of melt. In a thick section from 30 May 2002, Nicolaus *et al.* (2003) showed a typical layering of superimposed ice below a layer of metamorphic snow and on top of highly porous sea ice, as it exists during each melt season. Along with earlier measurements in the same year, it was concluded that 0.23 m of snow cover were transformed into 50-60 mm of superimposed ice.

The changes of surface characteristics result in a strong albedo decrease with time, once melt has started (Figs. 5a&b). Detailed *in situ* measurements of spectral

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surface reflectance and bulk snow and ice transmittance resolved reflectance and albedo decreases in different wavelength ranges according to snow metamorphosis and snow layer thinning as well as the role of the snow layer in attenuating solar radiation (Fig. 5b, see also Gerland *et al.* 1999; Winther *et al.* 2004). In 2002, mean surface albedo (running daily averages, calculated from global and reflected shortwave radiation) decreased strongly about 3 days after the onset of melt (day 147) from a level of above 0.75 down to 0.38 while the remaining surface snow melted (Fig. 5a). After all snow had melted, a dark clear superimposed ice surface remained. Only two days later, this surface began to deteriorate, resulting in a layer of coarse ice grains on the surface, leading to an albedo increase to values of 0.51. In 2003, no strong melt event was observed. Instead, the snow remained intact over the observation period. Consequently, the albedo did not drop as strongly as in the previous year (Fig. 5a).

Compared to typical multi-year sea ice, where the presence of large melt ponds dominates surface albedo in summer, the albedo of the investigated fast ice cover on Kongsfjorden is controlled by snow thickness, snow grain sizes, and the formation and decay of superimposed ice. The latter processes are based on wetting and melting of the snow cover, but here the surface consists of a water saturated layer of rotten snow and ice with puddles of variable size. The relatively flat surface topography, allows only weak lateral melt water flow, so that no larger and deeper melt ponds can develop (exception: around icebergs). However, detailed information on the fast ice properties in Kongsfjorden in the late stage of melting is sparse.

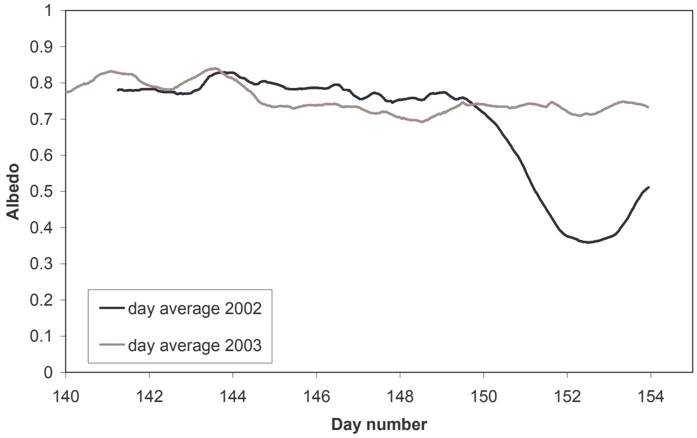

Fig. 5a: Time series of mean fast ice surface albedo for 2 weeks in 2002 and 2003 (running daily averages, calculated from shortwave global and reflected radiation).

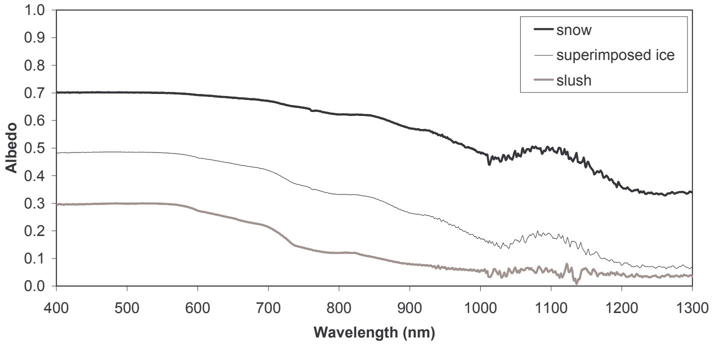

Fig. 5b: Spectral surface albedo over snow, superimposed ice, and slush on 4 June 2003. The two surfaces with reduced albedo were provided by removing the surface snow and superimposed ice layers manually.

Conclusions

The glaciological investigations of fast ice formation, development, and decay in Kongsfjorden have improved our understanding of some key processes relevant for sea ice and climate. This shows that Kongsfjorden is an excellent model case to study a number of processes relevant for large regions of Arctic and Antarctic. Process studies in this large-scale, open-air “laboratory” have the advantage that the ice can be accessed relatively easily and that climate data are continuously recorded at nearby research stations in Ny-Ålesund. Future studies will focus with more detail on the controlling parameters for fast ice development, the timing of formation, surface changes, melt onset and open water situation, as well as on quantitative descriptions and modelling of fast ice processes that change the energy and mass balance. Further, the Kongsfjorden fast ice as a research object in itself, and its coupling to the ocean and atmosphere, has led to the start of a long-term sea ice monitoring project at the Norwegian Polar Institute in 2003, including regular ice thickness drillings and daily visual observations from Zeppelinfjellet, a mountain near Ny-Ålesund (Fig. 1). Snow and ice properties in Kongsfjorden are also very relevant for studies of the Arctic ecosystem (Hop *et al.* 2002). Sea ice is a habitat for various biota (ice algae and ice underside fauna, seals, polar bears), and it influences indirectly other habitats, such as the seafloor with benthic flora and fauna, or by giving foxes access to the bird nesting places on islands in Kongsfjorden (Parker and Mehlum 1991 Mehlum 1991; Lydersen and Gjertz 1986). A marine laboratory is currently under construction in Ny-Ålesund which will further improve the infrastructure for interdisciplinary work at Kongsfjorden.

Acknowledgements

We thank many collaborators and helpers in the field and the station personnel of the Alfred Wegener Institute for Polar and Marine Research (Koldewey Station) and the Norwegian Polar Institute (Sverdrupstasjonen) in Ny-Ålesund, Svalbard, for their support in connection with the fieldwork campaigns in Kongsfjorden. Projects from where data were used were financed by the Research Council of Norway, the Norwegian Polar Institute, the EU Large Scale Facility programme Ny-Ålesund, and the Alfred Wegener Institute for Polar and Marine Research. The compilation of the manuscript was supported by the project “Determination of thickness and surface characteristics of sea ice” under the Mobility programme for research collaboration between Germany and Norway of the German Academic Exchange Service (DAAD, Project No. 313-PPP-N4lk) and the Research Council of Norway. Finally we are grateful to the reviewer H. Eicken and the editor C. Wiencke for constructive criticism that helped improving the manuscript.

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