The size and frequency of icebergs and bergy bits derived from tidewater glaciers in Kongsfjorden, northwest Spitsbergen

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Tidewater glaciers constitute over 1000 or 20% of the coast of Svalbard. The dimensions and frequency of the occurrence of icebergs and bergy bits produced from these tidewater glaciers in Kongsfjorden, northwest Spitsbergen, were measured during the summers of 1991 and 1992. In 1991, 35–40% of 275 observed icebergs and bergy bits were <0.5 m wide, and <10% exceeded 5 m in width. 70–80% of the freeboard measurements were <0.5 m and only 10–15% were >1 m in height. The largest observed freeboard was 6 m. In 1992, small icebergs were significantly less common. 50% of the observed icebergs were >10 m in width and >2 m in freeboard. This is interpreted to be the result of a major calving event prior to the 1992 observations. Side-scan sonar data on sea floor morphology showed frequent scouring by iceberg keels to a depth of 35 m, but no scouring below 40 m, thus defining the maximum iceberg keel depth and the depth to which sediment reworking by these keels occurs. Calculations of the melt rate of icebergs allows an estimation of the life expectancy of icebergs calved into Kongfjorden. Melting by forced convection lies between approximately 0.1 and a maximum of 1.0 m d^{-1}, depending on iceberg relative velocity, size and water temperature. Melting linked to wave action is also approximately 0.5–1.0 m d^{-1}. These calculations imply that icebergs of the dimensions commonly observed in Kongsfjorden will seldom survive travelling beyond the fjord mouth. Radar observations of iceberg occurrence from FS POLARSTERN during its summer 1991 circumnavigation of Svalbard also showed that no larger icebergs were escaping beyond the mouths of the major fjords of western and northern Spitsbergen. Iceberg derivation from Spitsbergen fjords is therefore not likely to be an important mechanism for sediment rafting and deposition on the continental shelf and in the deep ocean, but it is of significance to local fjord sedimentation. Comparison with evidence on iceberg dimensions from the Barents Sea and an East Greenland fjord shows that the larger icebergs there are derived from parent ice masses with quite different characteristics than those calving into the Spitsbergen fjords.

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Introduction

Tidewater glaciers (i.e. those with marine margins grounded below sea level) constitute over 1000 km or almost 20% of the coastline of the Svalbard archipelago (Dowdeswell 1989). Icebergs and smaller bergy bits (freeboard <5 m, width <10 m; Armstrong et al. 1966) produced at this ice-ocean interface carry with them debris which is released and deposited on the sea floor, often forming characteristic sedimentary structures and facies (Gilbert 1990). They therefore have both glaciological and glacial-geological significance in the study of the mechanism of mass loss from parent glaciers and ice caps and the process of sediment transfer from terresterial to marine environments. If iceberg keels contact the sea floor, scouring and associated sediment reworking also takes place.

This paper describes the dimensions (width and freeboard) of 295 icebergs and bergy bits derived from tidewater glaciers in Kongsfjorden, northwest Spitsbergen. The iceberg size-frequency distributions are compared with those from East Greenland fjords and the epicontinental Barents Sea. Calculations of iceberg melt rates and survival times are made, utilizing observations on fjord water temperature and iceberg velocity. The implications for iceberg survival, for iceberg sedimentation within the fjords of Spitsbergen, and for the transfer of iceberg rafted debris onto the continental shelf and into the deep ocean are also discussed. Although small icebergs are strictly termed bergy bits (Armstrong et al. 1966), we

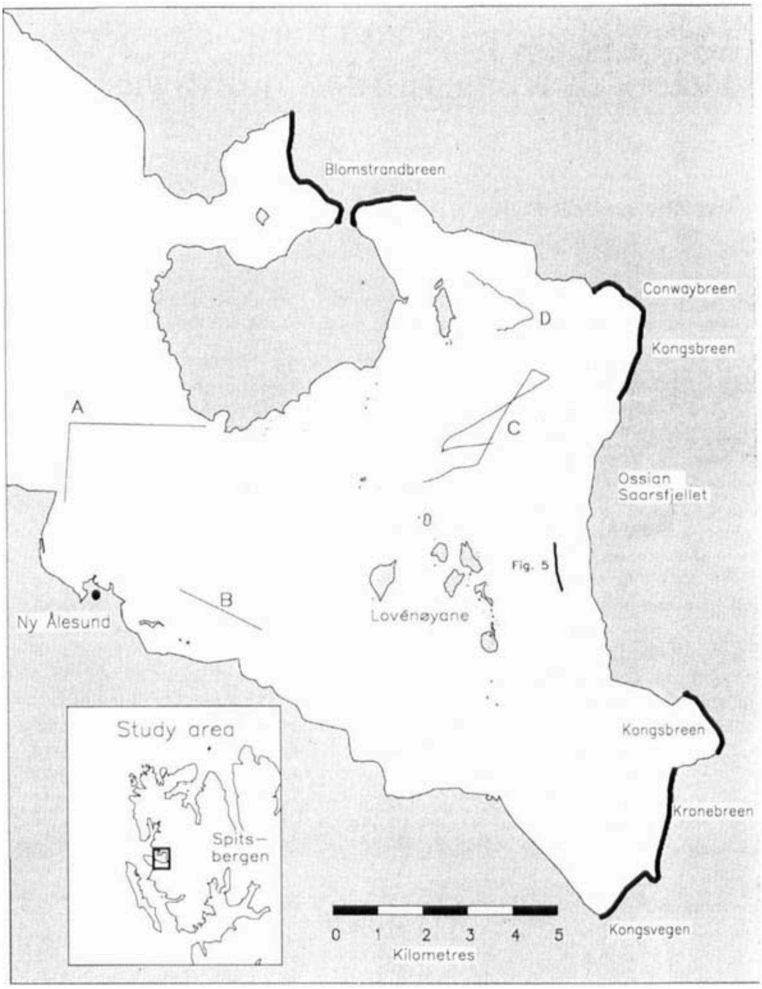

Fig. 1. Study area, inner Kongsfjorden, Svalbard. Thick lines indicate tidewater glacier termini. A, B and C indicate the transects along which iceberg size-frequency data were collected. Location of the side-scan sonar image (Fig. 5) is also shown.

will, for simplicity, refer to all floating glacier-derived ice as icebergs in this contribution.

Study area and methods

Observations on iceberg dimensions were made in the inner 10 km of Kongsfjorden, northwest Spitsbergen (Fig. 1), during the summers of 1991 and 1992. This fjord was selected for study because of the presence of five tidewater glaciers, of varying dynamic regime, which each calve icebergs into the fjord (Liestøl, 1988). A fast-flowing outlet glacier, a surge-type glacier in the quiescent phase, and several other glaciers are present. Radio-echo sounding measurements of ice thickness, ice surface profiles and offshore bathymetric data demonstrate that each of these glaciers is aground rather than floating (e.g. Dowdeswell et al. 1984; Hagen & Saetrang 1991). From maps of early expeditions and from a series of oblique and vertical aerial photographs from 1936 which are archived at the Norsk Polarinstitutt, it is possible to reconstruct the fluctuations of the tidewater margins of each glacier as far back as the turn of the century (Liestøl 1988).

Measurements of the maximum width and freeboard of 295 icebergs were made directly from a 7.5 m launch along three transects within the inner part of Kongsfjorden in 1991 and one transect in 1992 (Fig. 1). Navigation was provided by a Trimble Pathfinder GPS system. Iceberg dimensions ranged between widths of <0.5 m and a maximum of 30 m, and freeboards were of up to 15 m. Size-frequency distributions were then constructed for the parameters of iceberg width and freeboard along each of the transects (Figs. 2, 3 and 4). In general it is difficult to distinguish between the smallest fragments of glacier-derived ice and the sea-ice floes. Glacier origin was determined by the presence of ice deformation structures and the content of debris of heterogeneous grain size. Therefore, as the fjord is usually clear of ice in late July, when the first observations were made, the whole dataset is taken as representative of glacier derived ice.

Several other datasets relevant to the occurrence and behaviour of icebergs were also collected in and beyond the fjord during the field programme. These included the following:

1. Measurement of salinity and temperature with depth (CTD) at 42 stations in the fjord, using a Sensordata-200 CTD meter (P. Gilmour, pers. commun.). These data are used in the calculation of iceberg melt rates.
2. Measurement of iceberg velocities through survey from the shore of the fjord, under calm and stormy conditions (maximum wind speed 35 kts), in order to specify the range of drift speeds attained by icebergs within the fjord system. This information is also required in calculating iceberg melt rates.
3. A side-scan sonar survey (200 track km) of sea floor morphology in the inner fjord basin, undertaken using a Waverley Mark 3000 towfish operating at ranges of 150 or 300 m to either side of the vessel track (R. J. Whittington, pers. commun.). Side-scan imagery gives information on the depth to which scouring by iceberg keels extends.
4. Recordings of the locations and dimensions of icebergs encountered during a circumnavigation of Svalbard by the Alfred-Wegener Institute vessel FS POLARSTERN in early summer 1991 (Cruise ARKVIII/2) (M. Enall, pers. commun.). The ship's radar aboard POLARSTERN was used to measure iceberg dimensions (noting that bergy bits are difficult to detect using ship radar), following the method of Wadhams (1987) and Dowdeswell et al. (1992). The cruise included a period of four days outside Kongsfjorden, allowing us to extend our comments on iceberg occurrence in the 1991 summer beyond the inner fjord and onto the adjacent continental shelf.

In addition to these systematic observations, the collection of aerial photographs of Kongsfjorden held by Norsk Polarinstitutt was also examined for the presence of large icebergs. Reconnaissance observations were also made by fixed wing aircraft in both Kongsfjorden and the adjacent Krossfjorden.

Iceberg size-frequency: results

Iceberg widths

The size-frequency distribution of the maximum widths of 275 icebergs was similar for each of the three transects along which measurements were made in the summer of 1991 (Fig. 2). Between 35 and 40% of the bergs were less than 0.5 m wide, and less than 10% exceeded 5 m in width. The maximum observed iceberg width in Kongsfjorden was 30 m, but the histograms in Fig. 2 show that this was an extreme outlier. In general, there was a very rapid decrease in iceberg frequency with increasing size class. The tidewater glaciers of inner Kongsfjorden were, therefore, characterized by the production of relatively large numbers of small icebergs in 1991.

During July 1992, however, very few icebergs were observed in inner Kongsfjorden relative to the situation in 1991, and there was no longer a predominance of small bergs. Size-frequency information from a transect approaching Conwaybreen (Fig. 1) demonstrates this difference. Half the observed icebergs were in excess of 10 m in width (Fig. 4). The largest observed iceberg was 30 m wide, with a 5 m freeboard.

Examination of aerial photographs on scales of 1:50000 and 1:20000 in the Norsk Polarinstitutt collection for 1936, 1966, 1969, 1970, 1977 and 1990 confirmed that icebergs larger than 20–30 m in width are unusual in these waters. Reconnaissance flights over Kongsfjorden and the adjacent Krossfjorden in the springs of 1983 and 1987, and ship-board operations in Krossfjorden in the summers of 1986, 1987 and 1988, also indicate the presence of few larger icebergs. The largest iceberg observed over the entire period, about 100 m in diameter (Dowdeswell 1989), was close to the glacier Lilliehöökbreen in Krossfjorden.

Regular observations of iceberg occurrence from FS POLARSTERN during its summer 1991 circumnavigation of Svalbard also showed (over a 10 day period) that no larger icebergs were escaping

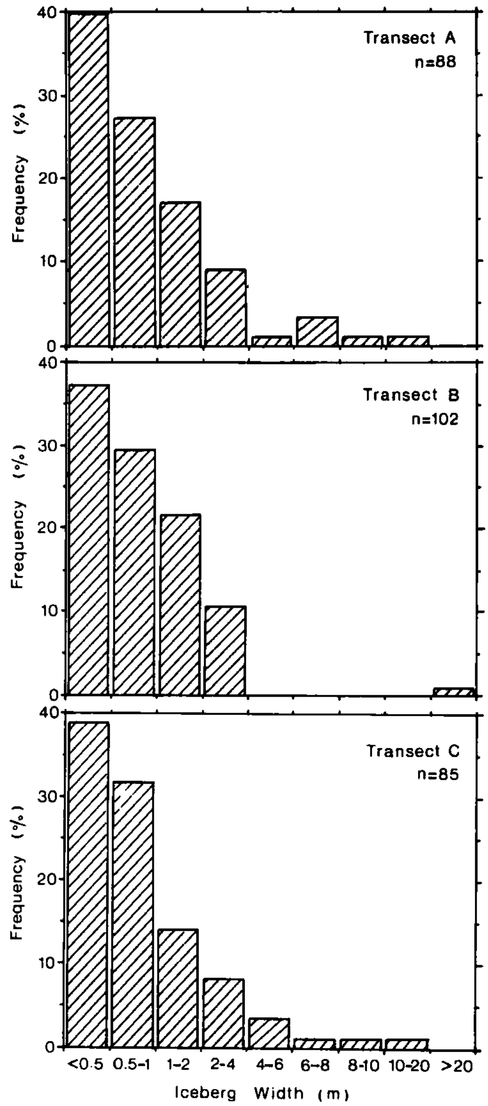

Fig. 2. Iceberg width-frequency for each of the three transects (A, B and C, Fig. 1) made in August 1991.

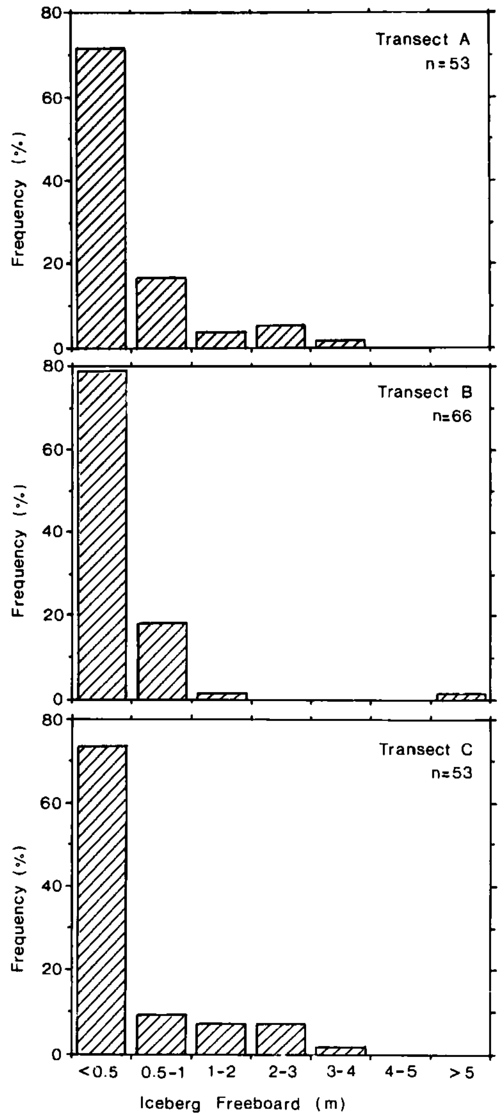

Fig. 3. Iceberg freeboard-frequency for each of three transects made in August 1991 (A, B and C, Fig. 1).

beyond the mouths of the major fjords of western and northern Spitsbergen, although each fjord has tidewater glaciers flowing into it. During this period no large icebergs were observed on the continental shelf to the west and north of Spitsbergen (Enall, pers. commun.), even though the ship's radar would be expected to identify icebergs of approximately 20 m in length to ranges of at least 8 nautical miles (Wadhams 1987; Dowdeswell et al. 1992). By contrast, three icebergs in excess of 100 m in width were observed by radar in the waters immediately east of Spitsbergen and Nordaustlandet (Enall, pers. commun.).

Iceberg freeboards and keel depths

The frequency distributions of 192 iceberg freeboards, obtained along four transects within inner Kongsfjorden (Fig. 1), follow a pattern similar to that for widths (Figs. 3 and 4). In the summer of 1991, the decrease in frequency was, however, even more marked with increasing size class.

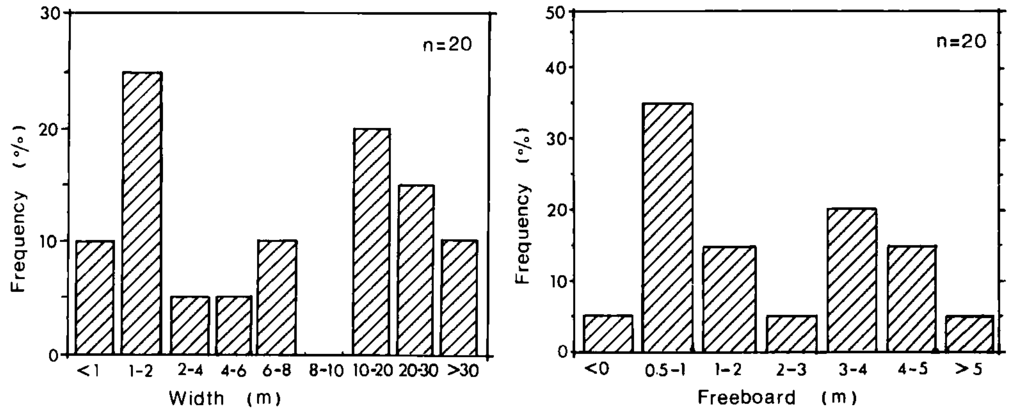

Fig. 4. Iceberg width and freeboard frequency distributions for the July 1992 transect (D, Fig. 1).

Between 70 and 80% of iceberg freeboard measurements were of less than 0.5 m and only 10 to 15% were above 1 m in height (Fig. 3). The largest observed freeboard was 6 m. By contrast, in 1992, 50% of the observed icebergs had freeboards in excess of 2 m, and the largest measured freeboard was 5 m (Fig. 4).

Iceberg keel depth can be calculated from observations of freeboard, given assumptions concerning the density and shape of the iceberg. However, the above-water morphology of the icebergs in Kongsfjorden, and indeed of the majority of icebergs derived from Spitsbergen tidewater glaciers (Dowdeswell 1989), is irregular. This irregularity means that, by contrast with tabular icebergs, the calculation of iceberg keel depth using a simple assumption concerning iceberg density is problematic.

An indirect method of deriving iceberg keel depths is provided by the study of side-scan sonar imagery, acquired over 200 track km of the sea floor of inner Kongsfjorden during the summer of 1991. These data on sea floor morphology showed that scours produced by iceberg keels occurred quite frequently to a depth of about 35 m, but that no scours were observed below 40 m (Fig. 5). Scours to this depth cannot be produced by the relatively thin fast ice cover (<2 m) that develops on the surface of Kongsfjorden during each winter and breaks up the following spring. A value of 40 m thus defines the maximum iceberg keel depth found in Kongsfjorden.

This estimate of maximum iceberg keel depth represents morphological evidence averaged over a time period controlled by the depth of scouring and the rate at which scours are buried by continuing sedimentation. A sedimentation rate of between 50 and 100 mm yr^{-1} was obtained by Elverhøi et al. (1983) from the area within 2 km of the present terminus of Kongsvegen and Kronebreen (Fig. 1). In more distal locations, within Kongsfjorden the sedimentation rate is 1–2 mm yr^{-1} (Elverhøi et al. 1983). Estimates of the minimum time interval represented by the scours imaged on the modern floor of Kongsfjorden can be derived by taking these sedimentation rates and assuming (1) that scours have a depth of 0.5 m and (2) that no image is observed on side-scan sonar records after burial to five times the scour depth. This gives an interval of approximately 25–50 years between scour formation and burial in the inner basin and from 1250–2500 years for those areas beyond the inner basin which are shallow enough for ice keel grounding to take place. In the latter areas, scours may be more likely to be destroyed by subsequent scouring than by burial.

Iceberg melt rates

Calculation of the rate of melting of icebergs allows the estimation of the life expectancy of the icebergs calved into Kongsfjorden. Seasonal variations in iceberg melting are not of importance here, since iceberg drift and calving are curtailed from late autumn to June by the presence of shorefast sea ice. Calculations are therefore made for summer season conditions only.

Several equations can be used to estimate ice-

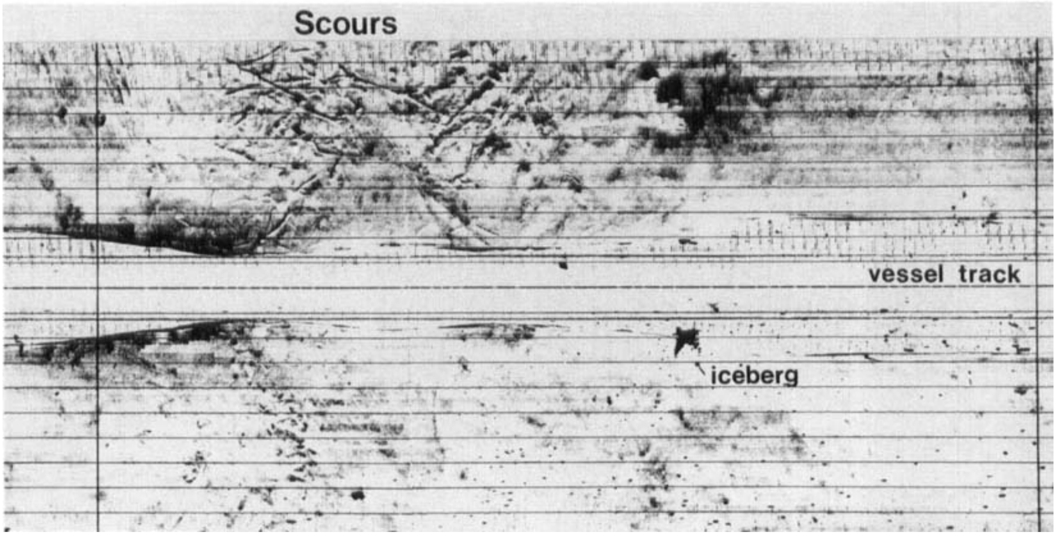

Fig. 5. Side-scan sonar image of the sea floor on the south side of inner Kongsfjorden (Fig. 1). Note the concentration of scours over a submarine ridge, where water depth is less than 40 m. The image represents 150 m to either side of the vessel track (i.e. 15 m per division). The distance between the two along-track divisions is 0.92 km or 0.5 nautical miles.

berg melt rate. Russell-Head (1980) gives the following empirical equation for iceberg basal melt rate (M_b in m s^{-1}) based on laboratory experiments with ice blocks in water of known temperature and normal ocean salinity, where:

$$M_b + 2.08 \times 10^{-7} (T_s + 1.8)^{1.5} \quad (1)$$

and T_s is seawater temperature. Our temperature and salinity with depth data from Kongsfjorden suggest a value of 3°C as representative of seawater temperature in the upper 10 m of the water column during summer. Using this figure, we obtain a melt rate of 0.19 m d^{-1} from equation 1. This equation has the advantage of being based on empirical measurements of small ice blocks (up to 1 m in length), similar to the size of the smaller icebergs recorded in Kongsfjorden (Figs. 2, 3 and 4). However, it takes no account of the relative velocity between an iceberg and the water surrounding it.

This effect, known as forced convection, is considered in an alternative equation (Weeks & Campbell 1973), where the melt rate at the base of an iceberg by this process (M_{bf} in m s^{-1}) can be found from:

$$M_{bf} = 6.74 \times 10^{-6} \, v_w^{0.8} \Delta T / X^{0.2}, \quad (2)$$

where v_w is free stream relative water velocity past an iceberg, ΔT is temperature difference between an iceberg and the surrounding water, and X is length of the iceberg. A number of calculations using a value of 3°C for ΔT, and varying both v_w and X, are given in Table 1, using iceberg velocity data from Kongsfjorden. For an iceberg of 0.5 m in length, melt rates vary from over 1 m d^{-1} for the highest observed speed (0.6 m s^{-1}) to about 0.05 m d^{-1} at very low velocities (0.01 m s^{-1}). It should be recognized that observed iceberg speed represents the *maximum* possible relative water velocity past an iceberg. In practice, drifting icebergs with only small keels will have a velocity similar to wind-driven surface water currents. Bergs with larger keels may also be affected by tidally driven currents at greater depth. Varying the seawater temperature up or down by 1°C results in a change in melt rate of approximately 0.06 m d^{-1} at a relative velocity of 0.05 m s^{-1} (Table 1). It should be noted that, for lower values of v_w (Table 1), the melt rate predicted by equation 2 is of a similar magnitude to that derived from equation 1.

Theoretical estimates of the amount of ice melted by waves at an iceberg waterline can also be obtained, if it is assumed that wave friction is related directly to wave heat transfer via a Reynolds analogy (El-Tahan et al. 1987). Taking the

Table 1. Iceberg melt rates by forced convection calculated from equation 2 using different values for relative water velocity, the temperature difference between an iceberg and the water column, and iceberg length.

Water Velocity ($m\ s^{-1}$)	Δ Temperature (°C)	Iceberg Length (m)	Melt Rate ($m\ d^{-1}$)
0.05	3	0.5	0.18
0.01	3	0.5	0.05
0.05	4	0.5	0.24
0.05	2	0.5	0.12
0.50	3	0.5	1.15
0.05	3	0.1	0.25
0.05	3	1.0	0.16
0.05	3	10.0	0.10

period and height of waves of sea state 1-2 (waves during summer 1991 were significantly higher than this on several occasions), and an assumption of 1 cm as the height of roughness elements on an iceberg surface (El-Tahan et al. 1987), a melt rate of around 0.5–1 m d^{-1} due to wave action is predicted even at these low sea states. Waterline melting will also lead to the calving of the overhanging slabs that result. El-Tahan et al. regard wave-induced melting to be the most important mechanism leading to rapid iceberg deterioration, based on studies in the Labrador Sea area.

The implications of these calculations on iceberg melting are that over 75% of icebergs (i.e. those <1 m in width and freeboard) are likely to melt within a day or two at the highest observed velocities (i.e. the maximum estimates for relative velocity), and that for all but the largest icebergs travelling at low relative velocities, melting will take place within one to two weeks. Given the relatively rapid rate of melting induced by wave action, even at quite low sea states, icebergs 10–30 m in length will deteriorate in less than a month. When it is remembered (1) that most of the larger icebergs (freeboard >2 m) observed in Kongsfjorden were grounded on shoals, (2) that most icebergs will follow a convoluted drift track through the fjord, and (3) that only 26% of a bathymetric section across the inner fjord is >20 m in depth, it is unlikely that the few large icebergs calved into Kongsfjorden will survive the journey to the continental shelf some 30 km in straight-line distance from the ice cliffs of Kongsvegen and Kongsbreen to the fjord mouth. The conclusion from these calculations is that almost all the icebergs produced by the tidewater glaciers flowing into Kongsfjorden are likely to melt within the fjord itself.

Discussion

Variability in iceberg size-frequency distributions

The significant differences in both iceberg width and freeboard between the 1991 and 1992 transects indicate that temporal variability in the size-frequency distribution of calved icebergs exists (Figs. 2, 3 and 4). However, the evidence both from these two summers and from reconnaissance and aerial photographic information over a longer period suggests that icebergs which exceed 30 m in width are seldom produced by these tidewater glaciers.

As systematic monitoring of tidewater glacier termini and recording of shifts in size-frequency were not carried out through the entire summer periods, it is difficult to provide definitive reasons for the contrasts, both in the absolute numbers of icebergs present and their widths and freeboards, between the 1991 and 1992 observations. A possible explanation for the larger size and smaller total numbers of observed icebergs in 1992 is that they were the result of a major calving event, probably from the terminus of Conwaybreen (Fig. 1), just prior to our observations. It is unclear, however, why such a calving event should not produce a significant number of very small bergy bits derived from the calving process itself. The lack of observations through time constrains further discussion of the reasons for these differences, but it is clear that over both periods of observation significant numbers of icebergs larger than 30 m in width were not produced.

Ice dynamics

The dynamics of the parent ice mass are likely to affect both the dimensions of calved icebergs and their rate of production. Liestøl (1988) suggests that the bulk of present-day iceberg production in Kongsfjorden is from Kronebreen (Fig. 1). This is because it is known to be flowing relatively rapidly. Field surveys on the lower part of Kronebreen have recorded velocities reaching over 4 m d^{-1} in summer and 1.5 m d^{-1} in winter (Voigt 1969). By contrast, velocities on the adjacent Kongsvegen (Fig. 1) were two orders of magnitude lower. The surface of the terminus of Kronebreen is highly crevassed, suggesting that calving will produce many small icebergs rather than occasional larger ones. Hughes (1992) has developed a theory of iceberg calving from tidewater glaciers in which the calving rate is controlled by bending creep behind the terminal ice cliff, and depends on ice cliff height, forward bending angle, crevasse spacing and water depth.

Vinje (1989) notes that interannual variability in the occurrence of icebergs in the Bàrents Sea may be linked with surge activity in eastern Svalbard. Unfortunately, the effects of surges on iceberg size and frequency cannot be investigated in Kongsfjorden today. Several glaciers within the fjord are known to be of surge-type (Kronebreen, Kongsvegen and Blomstrandbreen; Fig. 1), but they are each in the relatively long quiescent phase of the surge cycle at present (Liestøl 1988). However, analysis of aerial photographs of a number of Svalbard tidewater glaciers during the active phase shows that they are very heavily crevassed, and suggests that the main effect is the production of small icebergs of irregular shape in very large numbers (Dowdeswell 1989).

Tidewater glaciers of a few kilometers in terminus width are found in each of the major fjord systems in Spitsbergen: Hornsund, Van Keulenfjorden, Van Mijenfjorden, Isfjorden, Kongsfjorden-Krossfjorden, Woodfjorden-Liefdefjorden and Wijdefjorden. We suggest that each of these fjord systems is characterized by the production of relatively large numbers of bergy bits and few large icebergs, broadly similar in dimensions to the icebergs and bergy bits observed in Kongsfjorden (Figs. 2, 3 and 4). This hypothesis is based on (1) the similarity in ice dynamics between the tidewater glaciers entering these fjord systems and (2) aerial reconnaissance and photographs of these fjords (cf. Dowdeswell 1989).

It should be emphasized that certain ice masses in eastern Svalbard may produce significant numbers of relatively large (>100 m length) tabular icebergs. This is particularly the case for the long lengths of terminal ice cliffs present around eastern Nordaustlandet and Kvitøya (e.g. figure 4 in Dowdeswell 1989). It has also been observed that Negribreen, a tidewater glacier at the north end of Storfjorden, east Spitsbergen, which last surged in 1935–36 (Vinje 1989), has produced a number of tabular icebergs in excess of 100 m length since that time (e.g. figure 9d in Dowdeswell 1989).

Comparison with icebergs in the Barents Sea and East Greenland

Evidence on the size-frequency distributions of both iceberg widths and freeboards is available from the Barents Sea, east and south of Svalbard (Voevodin 1972), and from East Greenland fjords (Dowdeswell et al. 1992). Histograms for iceberg width and freeboard distributions in each area are shown in Fig. 6. For both areas over 50% of observed icebergs were of width greater than 50 m, and over 90% had freeboards in excess of 5 m (Fig. 6). Vinje (1989) also reported the width and freeboard of 54 icebergs observed in the Barents Sea using SPOT panchromatic satellite imagery (nominal resolution 10 m) during April 1987. Maximum iceberg width ranged between 20 and 200 m, with freeboard between 3 and 17 m. The size distribution is clearly truncated at the low end by the limitation imposed by satellite sensor resolution. Each of these studies indicates, however, that the majority of observed Barents Sea and East Greenland icebergs were significantly larger than the largest icebergs recorded in Kongsfjorden (Figs. 2, 3 and 4).

While it is undoubtedly the case that the icebergs from these other areas are in general larger than those derived from tidewater glaciers entering Spitsbergen fjords, it should be pointed out that no attempt was made in these other studies to measure the full range of iceberg sizes floating in the water. Measurement of icebergs within Vikingebugt in East Greenland did not include the dimensions of icebergs less than 20 m in width, although large numbers were present in this 10 km-long inlet with a tidewater glacier at its head, located within the Scoresby Sund fjord system (Dowdeswell et al. 1992). It is likely that fewer small icebergs were present in the Barents Sea, which is a significantly more ice distal environment. Here, bergy bits, similar to those

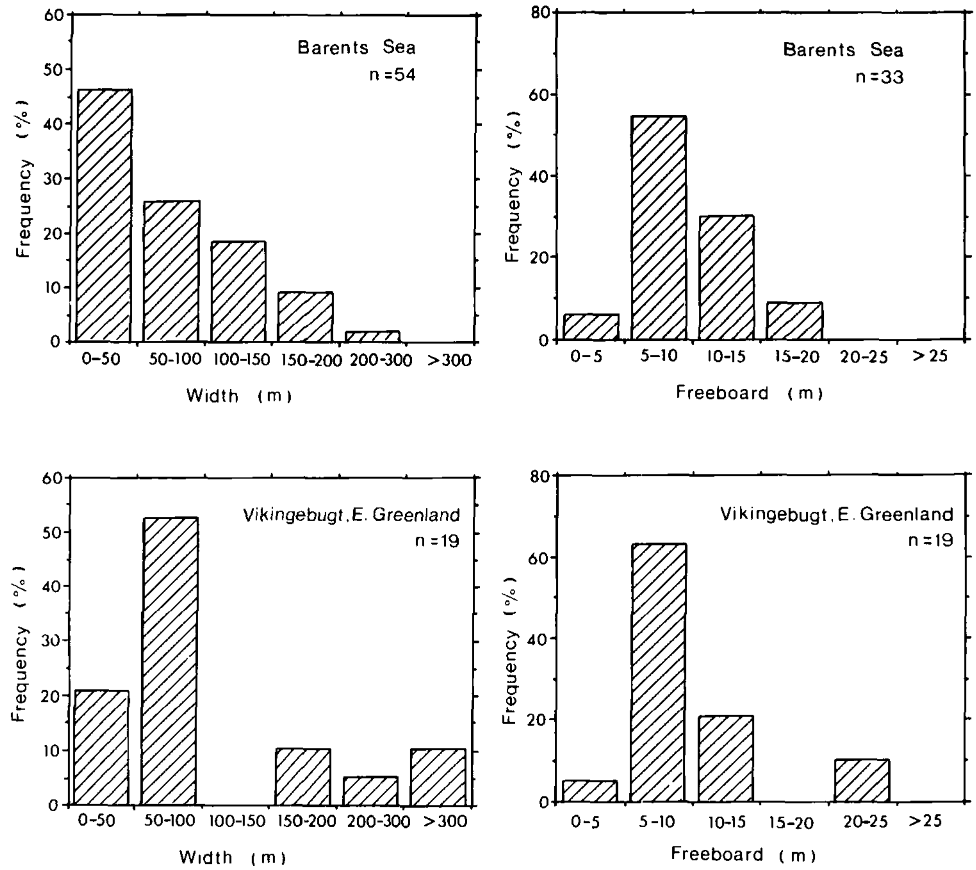

Fig. 6. Iceberg width and freeboard frequency distributions for Vikingebugt in East Greenland (Dowdeswell et al. 1992) and the Barents Sea (Voevodin 1972).

at the lower end of the range observed in Kongsfjorden, are likely to have been produced by the icebergs themselves in association with wave undercutting, ice cliff failure and berg fragmentation.

Implications for sedimentation

The sizes and frequency of occurrence of icebergs in Kongsfjorden and other Spitsbergen fjords have several implications for the nature of sedimentation, including the rate of sediment delivery, the distance of sediment transport by iceberg rafting, and the importance or otherwise of seafloor sediment reworking by iceberg keels.

Significant numbers of the icebergs observed in Kongsfjorden contain included debris. A detailed sampling programme in the adjacent fjord of Krossfjorden has demonstrated this more quantitatively (Dowdeswell & Dowdeswell 1989). Given that the calculations presented earlier suggest that most icebergs calved into Kongsfjorden will melt within the fjord, this implies that all the debris held in these icebergs will also be released to contribute to sedimentation within the fjord. Dowdeswell & Dowdeswell (1989) used a simple model to calculate the likely rate of sediment delivery to the region of Kongsfjorden inland of Ny-Ålesund (Fig. 1), making assumptions about the thickness of debris-rich basal ice and the concentration of sediment within this ice. These calculations, estimated to be of order of magnitude accuracy, suggested that an average of between about 5 and 8 mm a^{-1} of sediments would be deposited in this inner area of Kongsfjorden.

The calculations on the rate of iceberg melting also imply that icebergs of the sizes commonly observed in Kongsfjorden will seldom survive travelling beyond the fjord mouth. This, in turn, means that sedimentation on the continental shelf west of Spitsbergen is unlikely to be affected significantly by the input of iceberg rafted sediments under modern environmental conditions. This statement does not, however, rule out the occurrence of occasional dropstone recovery in sediment cores from the shelf, resulting from far-travelled larger icebergs or from shore-fast sea ice escaping seaward after breakup.

The relatively low freeboards that typify icebergs calved into Kongsfjorden (Figs. 3 and 4) imply that the scouring and reworking of fjord sediments by iceberg keels will operate only in relatively shallow water. Side-scan sonar imagery of the sea bed in Kongsfjorden demonstrates that scour marks are not present in water depths exceeding 40 m (Fig. 5). In shallower waters scour marks are common and significant sediment reworking will take place. An analysis of a 10 m contour interval bathymetric map of inner Kongsfjorden (inshore of Ny-Ålesund, Fig. 1) shows that only about 8% of the sea floor in this area is less than 40 m in depth. The area affected by iceberg keels is, therefore, of restricted extent in Kongsfjorden because of the deep and steep-sided nature of the fjord. This morphometry is similar to that in the fjords of Spitsbergen in general.

This situation contrasts with that on a number of continental shelf areas in the polar regions, where scouring by iceberg keels is a very significant sedimentary process over extensive tracts of the sea floor. These are areas where large tabular icebergs with keel depths of up to several hundred metres impinge upon the sea bed. Examples include the Labrador Shelf (Woodworth-Lynas et al. 1985; Josenhans et al. 1986) and Scoresby Sund and the adjacent continental shelf off East Greenland (Dowdeswell et al. 1991, 1992).

Conclusions

The variety of dynamic behaviour exhibited by the five tidewater glaciers entering Kongsfjorden, northwest Spitsbergen (Fig. 1), makes the area suitable for investigating the dimensions of the icebergs produced there. As these glacier termini are not floating, this precludes the production of large, tabular icebergs. The following main conclusions can be drawn from our observations of the size-frequency distributions of icebergs and berg bits in Kongsfjorden; they are likely to be applicable to the major fjord systems on the western and northern coasts of Spitsbergen:

1. Few icebergs greater than 20 m in length and 5 m in freeboard are produced from the tidewater glaciers entering Spitsbergen fjords (Figs. 2, 3 and 4).
2. Very few of these icebergs are likely to reach the open ocean. This is a result of their relatively small dimensions and the relatively warm waters into which they are released.
3. Icebergs and bergy bits derived from Spitsbergen fjords are unlikely to be an important mechanism for sediment rafting and deposition on the continental shelf and in the deep ocean, but are of significance to local fjord sedimentation (cf. Dowdeswell & Dowdeswell 1989).
4. Scouring and reworking of the fjord floor by iceberg keels takes place to a depth of 40 m (Fig. 5) This maximum in scour depth also provides a record of maximum iceberg keel dimensions.
5. Comparison with evidence on iceberg dimensions from the Barents Sea and an East Greenland fjord (Fig. 6) shows that the much larger icebergs found there are derived from parent ice masses with significantly different characteristics from those entering Spitsbergen fjords.

A final question, left unanswered by this study, concerns the possible sources of icebergs which, together with sea ice, transport ice rafted sediment into the Barents Sea and the Arctic Basin. It is clear from our work that the small icebergs and bergy bits calved from Spitsbergen tidewater glaciers are unlikely to make any contribution of significance. More likely source areas for icebergs entering the Barents Shelf and the Eurasian sector of the Arctic Basin are, first, the highly glacierized islands of the Russian Arctic archipelagoes Frans Josef Land and Severnaja Zemlja and, secondly, a more minor contribution from the large ice caps on Nordaustlandet and Kvitøya in northeastern Svalbard.

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