Chapter 3
Eurasian Arctic Ice Shelves and Tidewater Ice Margins

Julian A. Dowdeswell

Abstract Despite the presence of about 4000 km of marine-terminating glaciers and ice caps in the Eurasian Arctic, there are few floating ice shelves. Neither are there extensive areas of multi-year shorefast sea ice which might thicken into composite ice shelves themselves. The archipelagos of Severnaya Zemlya and Franz Josef Land contain some ice shelves in addition to grounded tidewater ice fronts. The largest Eurasian Arctic ice shelf was the Matusevich Ice Shelf, Severnaya Zemlya, at about 240 km^2 with a drainage basin of about 1100 km^2; this ice shelf largely broke up in 2012. In Franz Josef Land, a number of ice caps have smooth and very low surface gradient seaward margins, covering over 300 km^2 or 2% of the total area of the ice caps in the archipelago. These low-gradient areas are located mainly in relatively protected embayments and produce large tabular icebergs of up to several kilometres in length. Whether individual areas are floating in hydrostatic equilibrium or are simply close to buoyancy, they provide the major modern source of tabular icebergs to the Barents Sea. Svalbard has about 860 km of coastal ice cliffs, but almost none of the ice margin appears to be afloat. There may be short periods, during the active phase of the surge cycle, where marine margins become afloat. Neither is there evidence that the margins of the marine-terminating glaciers on Novaya Zemlya are floating. Twenty-five to fifty percent of the bed of the three largest ice caps in the Eurasian Arctic lies below sea level. Thus, in a warming Arctic, the ice margin would eventually retreat onto land, curtailing mass loss by iceberg production and providing a break on rapid ice-cap disintegration through calving.

**Keywords** Ice shelves • Tidewater glaciers • Eurasian Arctic • Icebergs • Sea ice

J.A. Dowdeswell (✉)
Scott Polar Research Institute, University of Cambridge, Cambridge, UK
e-mail: jd16@cam.ac.uk

3.1   Introduction

Glaciers and ice caps with extensive marine margins cover an area of about 90,000 km^2 in the Eurasian Arctic archipelagos (Fig. 3.1; Dowdeswell 1995; Dowdeswell and Hagen 2004). In western Eurasia, Svalbard has an ice cover of about 36,500 km^2, representing about 60% of its land area (Hagen et al. 1993). Austfonna, in north-eastern Svalbard, is the largest ice cap in the whole Eurasian Arctic at about 8000 km^2 (Dowdeswell 1986; Dowdeswell et al. 2008). East of Svalbard, the Russian Arctic archipelagos of Franz Josef Land, Severnaya Zemlya and Novaya Zemlya hold about 52,000 km^2 of ice (Moholdt et al. 2012a), with glacierized areas of 85%, 50% and 30%, respectively (Dowdeswell et al. 2010). In the Russian Far East, ice totalling less than 100 km^2 is present in the DeLong archipelago east of the New Siberian Islands (Verkulich et al. 1992).
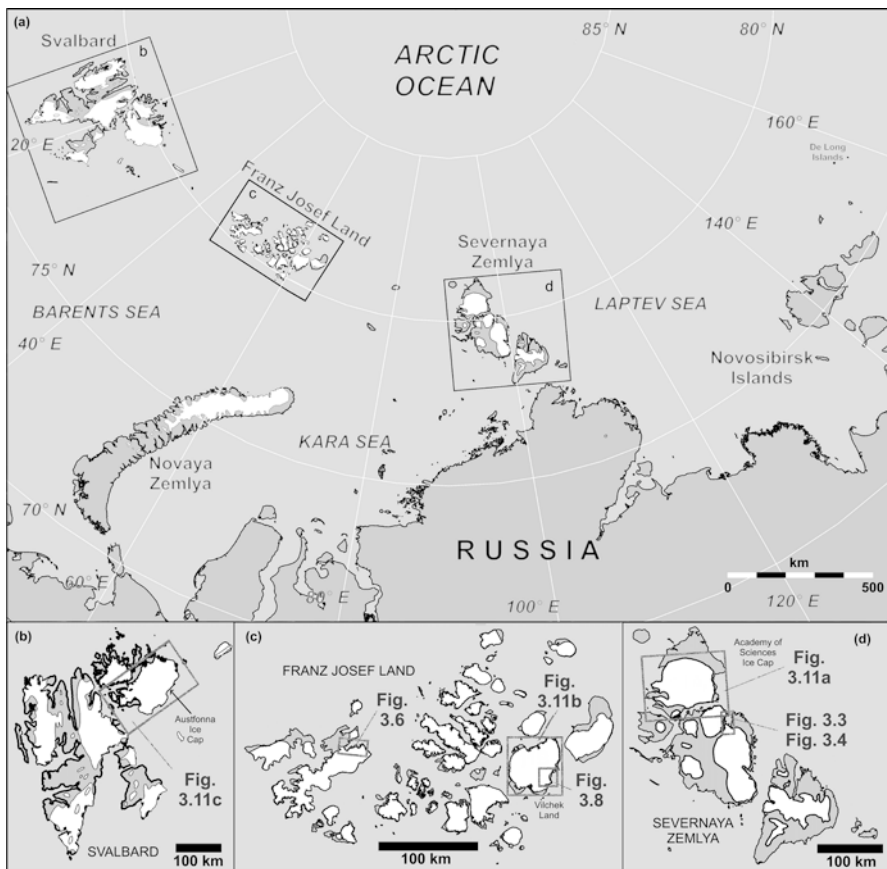
Fig. 3.1 (**a**) Map of the Eurasian Arctic showing the locations of the island archipelagos and the distribution of ice caps and glaciers. (**b**) Svalbard. (**c**) Franz Josef Land. (**d**) Severnaya Zemlya. The locations of several subsequent figures are shown (numbered on parts **b**, **c** and **d**)
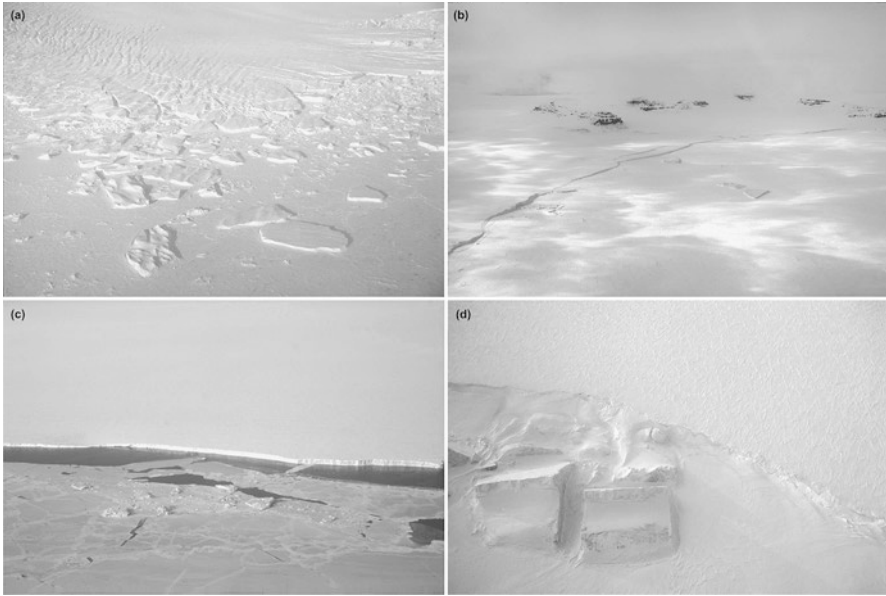
Fig. 3.2 Oblique aerial photographs of marine ice margins and icebergs calved from Eurasian Arctic ice caps. (**a**) Large numbers of tabular icebergs produced from a fast-flowing and probably floating ice stream on the east side of Academy of Science Ice Cap, Severnaya Zemlya, May 1998 (Dowdeswell et al. 2002). (**b**) Tabular iceberg about 0.5 km long embedded in shorefast sea ice in Franz Josef Land, May 1994. Note the new icebergs being produced at the calving margin of a low-profile ice cap. (**c**) Icebergs of irregular shape calved from the grounded margin of the Austfonna ice cap in eastern Svalbard in May 1983. The ice cliffs are about 30 m high. (**d**) An almost vertical view of the calving margin of Nergibreen in eastern Spitsbergen, May 1983. Several icebergs of almost 0.5 km across have been calved and are trapped in winter shorefast sea ice (Photographs: J.A. Dowdeswell)

Given the relatively high proportions of ice-covered land in the Eurasian Arctic islands, ice reaches the sea along much of this coastline (e.g. Fig. 3.2). Overall, there are approximately 4000 km of coastal ice cliffs in the Eurasian Arctic (Sharov 2005). There are about 860 km of marine ice cliffs in Svalbard (Blaszczyk et al. 2009), 2500 km in Franz Josef Land, 490 km in Severnaya Zemlya and 200 km in Novaya Zemlya (Sharov 2005). Comparisons between recent satellite datasets and maps produced from aerial photographs acquired in the 1950s suggest that the length of this ice-ocean interface has declined by about 8% (Sharov 2005), presumably reflecting the general retreat and thinning of glacier and ice-cap margins over this period (Dowdeswell and Hagen 2004; Carr et al. 2014; Melkonian et al. 2016).

The character of the margins of glaciers and ice caps in the Eurasian Arctic is a fundamental control on their mass balance (Hagen and Reeh 2004). For glaciers and ice caps that terminate on land, mass loss is almost entirely through surface melting and runoff. Where ice reaches the sea, the calving of icebergs and the melting of

vertical ice cliffs provide additional mechanisms of mass loss (e.g. Weeks and Campbell 1973; Rignot et al. 2010). If a marine ice margin is afloat, a further increment of mass loss takes place by melting at the floating underside of the ice shelf. Rates of basal ice-shelf melting can reach tens of metres per year (e.g. Rignot and Kanagaratnam 2006; Enderlin and Howat 2013). The sensitivity of ice caps and glaciers to projected climate warming is also linked to whether they are marine- or land-terminating. Eurasian Arctic ice masses whose coastal margins are likely to retreat onto land will decay more slowly than those marine-based ice masses where the retreating margin remains a marine one and, thus, mass loss by iceberg production and melting of the ice-ocean interface continues (e.g. Dowdeswell et al. 2008). In this contribution, the glaciers and ice caps of the Eurasian Arctic are described and discussed in the context of their marine margins and, in particular, the presence or otherwise of floating ice shelves.

3.2   Identification and Terminology for Floating and Grounded Ice

The terminology used here to describe the margins of glaciers and ice caps ending in marine waters is as follows. When the term 'ice shelf' is used in the context of marine-terminating glacier ice, the margin is observed or interpreted to be floating. The term 'ice tongue' has also been used by some researchers to describe floating glacier ice that is constrained by valley walls, with a floating portion that is long relative to its width (Hambrey 1994). When the term 'tidewater' is applied in this contribution, it implies that the marine ice margin is observed or interpreted to be grounded below sea level. When neither term is used in the context of marine ice cliffs, there is no implication that the margin is either grounded or afloat; it simply ends in the sea and it is not known whether or not the margin is grounded.

3.3   Floating Ice Shelves in the Eurasian Arctic

Despite the presence of about 4000 km of marine-terminating glaciers and ice caps in the Eurasian Arctic (Sharov 2005), very few areas of floating ice shelves fed by flow from glaciers and ice caps have been reported (Fig. 3.2). Neither do there appear to be extensive and thick areas of multi-year shorefast sea ice, similar to those making up the so-called ice mélange or sikussak of Greenland fjords (e.g. Reeh et al. 1999; Dowdeswell et al. 2000; Amundson et al. 2010; Reeh 2017), or significant parts of the northern Ellesmere Island ice shelves in Canada (e.g. Jeffries 2017). Shorefast sea ice seldom lingers through the Eurasian Arctic summer.

The Russian Arctic archipelagos of Severnaya Zemlya and Franz Josef Land appear to contain some ice shelves in addition to grounded tidewater ice

fronts (Fig. 3.2a, b), whereas the ice-ocean interface in Svalbard and Novaya Zemlya consists of grounded ice alone (Fig. 3.2c). The marine margins of the glaciers and ice caps in the four major archipelagos of the Eurasian Arctic are now described in turn, with particular reference to the presence of floating ice.
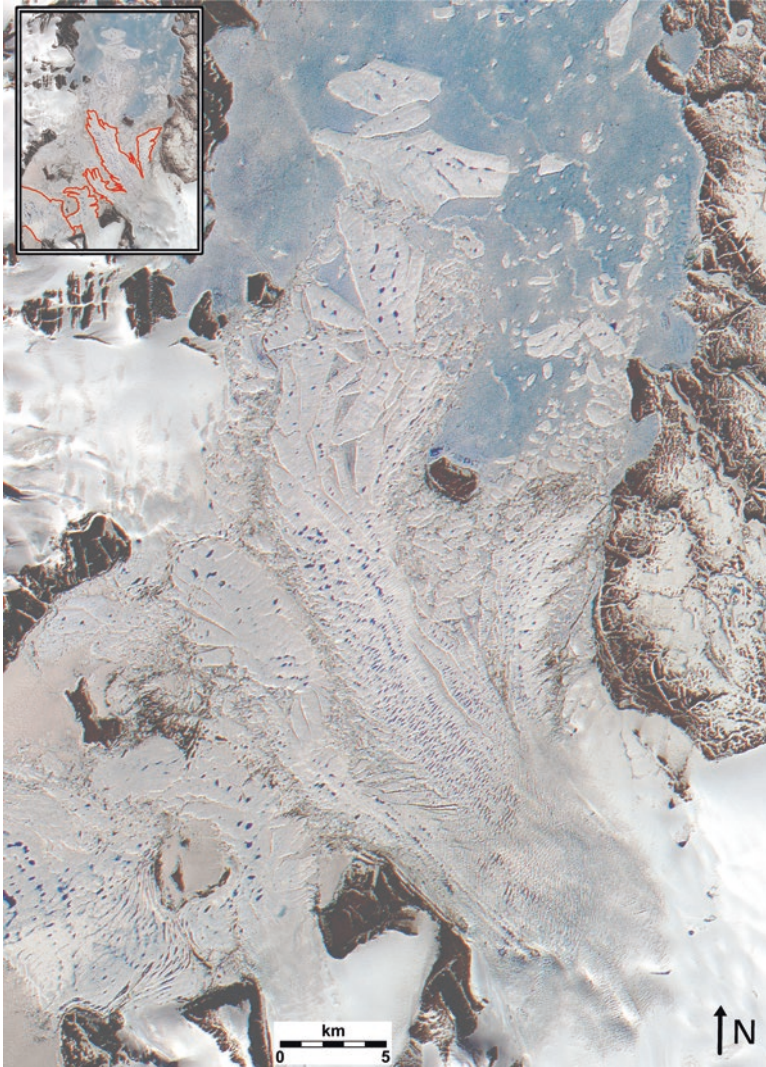
3.3.1 Severnaya Zemlya

The best-known ice shelf in the Eurasian Arctic is the Matusevich Ice Shelf, located in Severnaya Zemlya (Figs. 3.1d, 3.3, 3.4) (Williams and Dowdeswell 2001). In fact, ice in two areas of the archipelago is reported to be floating, according to the Russian Glacier Inventory (Govorukha et al. 1980). The more extensive of these ice shelves was the Matusevich Ice Shelf, which occupied the Matusevich Fjord on the northeast coast of October Revolution Island, centered on 79° 54'N, 98° 10'E. An ASTER image of the ice shelf is shown in Fig. 3.3. The fjord is almost 50 km long, with a maximum width of 12 km. The Matusevich Ice Shelf had an area of approximately 240 km^2 of floating ice in 1955 (Govorukha et al. 1980), with a surface slope of <0.2° near its margin (Fig. 3.5). Ice from a total of eight outlet glaciers from five source regions drains into Matusevich Fjord from the Rusanova and Karpinsky ice caps (Fig. 3.3). The total area of ice feeding the ice shelf was about 1100 km^2 in 1994 (Williams and Dowdeswell 2001). Terminus fluctuations of the Matusevich Ice Shelf appear to be cyclical, with a weak periodicity of about 30 years (Fig. 3.4f) (Williams and Dowdeswell 2001). This cyclicity is interpreted to be a result of the nature of iceberg calving from the ice shelf. Iceberg production is by the occasional breaking off of large tabular icebergs, of up to several kilometres in length (Fig. 3.4).

Between 10 August and 7 September 2012, the Matusevich Shelf largely broke up (Willis et al. 2015). This has resulted in the rapid thinning and speed-up of the outlet glaciers of the adjacent ice caps that fed the ice shelf. It is not yet clear whether the ice shelf may begin to grow again in the protected inlet beyond the present glacier margins (Fig. 3.3), as it has done after previous fluctuations in area over the twentieth century. This will probably depend on future atmospheric and ocean temperatures in the wider Russian Arctic (e.g. Walsh 2014).

A second ice shelf in Severnaya Zemlya, identified as ice mass No. 7 in the Russian Glacier Inventory (Govorukha et al. 1980), has a much smaller floating area of about 11 km^2 at the northeastern marine margin of the Academy of Sciences Ice Cap on Komsomolets Island (Fig. 3.1d). Many large tabular icebergs, of hundreds of metres in length, have been imaged calving from this floating ice margin (Fig. 3.2a; Moholdt et al. 2012b). Low gradient ice-surface profiles derived from 1950s Russian aerial photographs (Dowdeswell et al. 1994), together with the occurrence of a number of areas of open seawater bounding the larger Matusevich Ice Shelf (Zinger and Koryakin 1965), and radio-echo sounding data from Glacier No. 7 (Govorukha et al. 1980), have been used to confirm that these ice masses are afloat (Fig. 3.5).

Fig. 3.3 ASTER image of the Matusevich Ice Shelf acquired on 25 June 2005. Areas of floating ice shelf are shown are outlined in *red* in the inset. The ice shelf is fed from ice caps on Komsomolets and October Revolution islands in the Severnaya Zemlya archipelago (located in Fig. 3.1d). This ice shelf is the largest expanse of floating glacier ice in the Eurasian Arctic (Williams and Dowdeswell 2001). It is possible that some of the brash ice and sea ice in the areas between the icebergs and components of the floating ice shelf remain for more than a single year, forming so-called sikussak similar to that found in some Greenland fjords
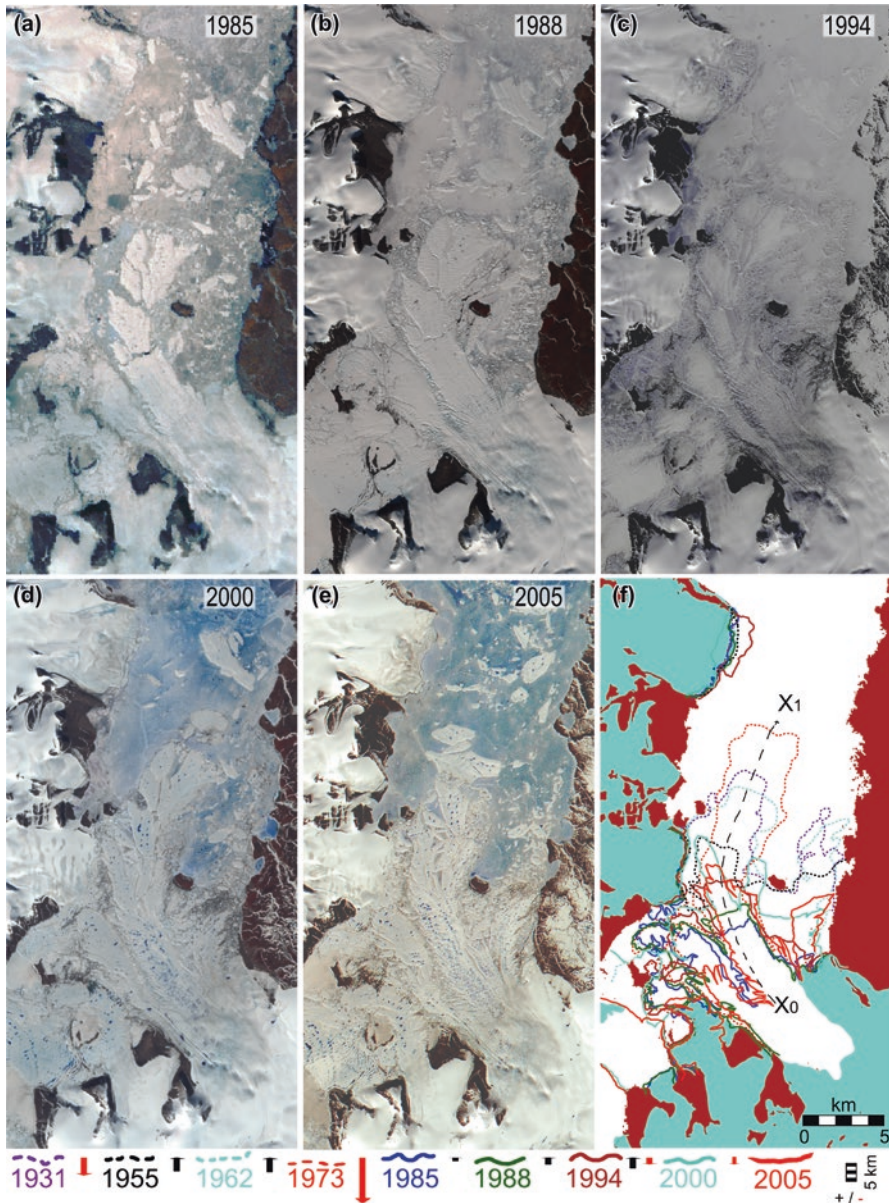
Fig. 3.4 Five satellite images of the Matusevich Ice Shelf, and adjacent icebergs derived from it, located between Komsomolets and October Revolution islands in the Russian archipelago of Severnaya Zemlya (located in Fig. 3.1d). (**a**) 12 August 1985 (Landsat TM image, Path/Row 170/002). (**b**) 26 August 1988 (Landsat TM image, Path/Row 164/003). (**c**) 20 June 1994 (Landsat TM image, Path/Row 168/002). (**d**) 9 July 2000 (Landsat ETM+ image, Path/Row 165/002). (**e**) 25 June 2005 (ASTER image). (**f**) The positions of the ice-shelf margin mapped for 1931, 1955, 1962, 1973, 1985, 1988, 1994, 2000 and 2005 (bare land is *brown* and grounded ice caps are *blue*). Changes in margin position were measured along transect X_0 to X_1. *Arrows* at the *bottom* of the diagram show the magnitude of advance (*black arrow*) or retreat (*red arrow*) between each period
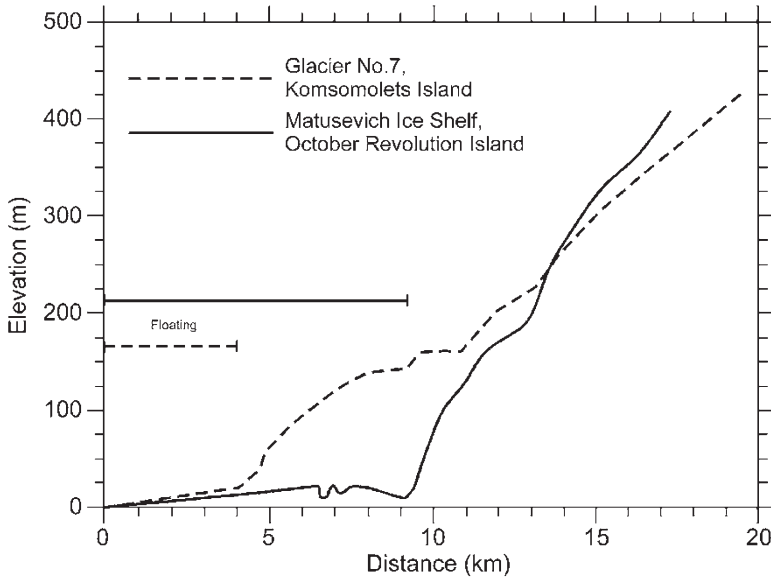
Fig. 3.5 Ice surface profiles from two ice shelves and their parent drainage basins on Severnaya Zemlya, derived from analysis of Russian aerial photographs from the 1950s. The Matusevich Ice Shelf is imaged in Fig. 3.3, and the smaller ice shelf on Komsomolets Island is fed by an eastern outlet of the Academy of Sciences Ice Cap (Fig. 3.2a) (Modified from Dowdeswell et al. 1994, Copyright Regents of the University of Colorado)

3.3.2 Franz Josef Land

There is some controversy in the early Russian literature as to the occurrence of ice shelves in Franz Josef Land. Spizharskiy (1936), Shumskiy (1949), and Govorukha (1968) each suggest that some small ice shelves may be present, whereas Grosswald et al. (1973) argue that none exist. Little direct evidence is offered in support of either case, although Govorukha (1968) states specifically that an ice shelf is present in the northeast of George Land (Figs. 3.6, 3.7).

While examining digital Landsat Thematic Mapper (TM) and Multispectral Scanner (MSS) satellite imagery of Franz Josef Land, a number of ice caps with smooth and apparently very low surface gradients at their seaward margins were observed (Figs. 3.6 and 3.7) (Dowdeswell et al. 1994). These areas were often associated with the production of relatively large tabular icebergs (Fig. 3.2b). The areas are dynamically part of the parent ice mass, and have a marked break of slope at their inner margins. Most, although not all, of the low gradient margins are located in relatively protected embayments (Fig. 3.6), rather than along sections of open coastline, and often have relatively deep water offshore. These flat features account
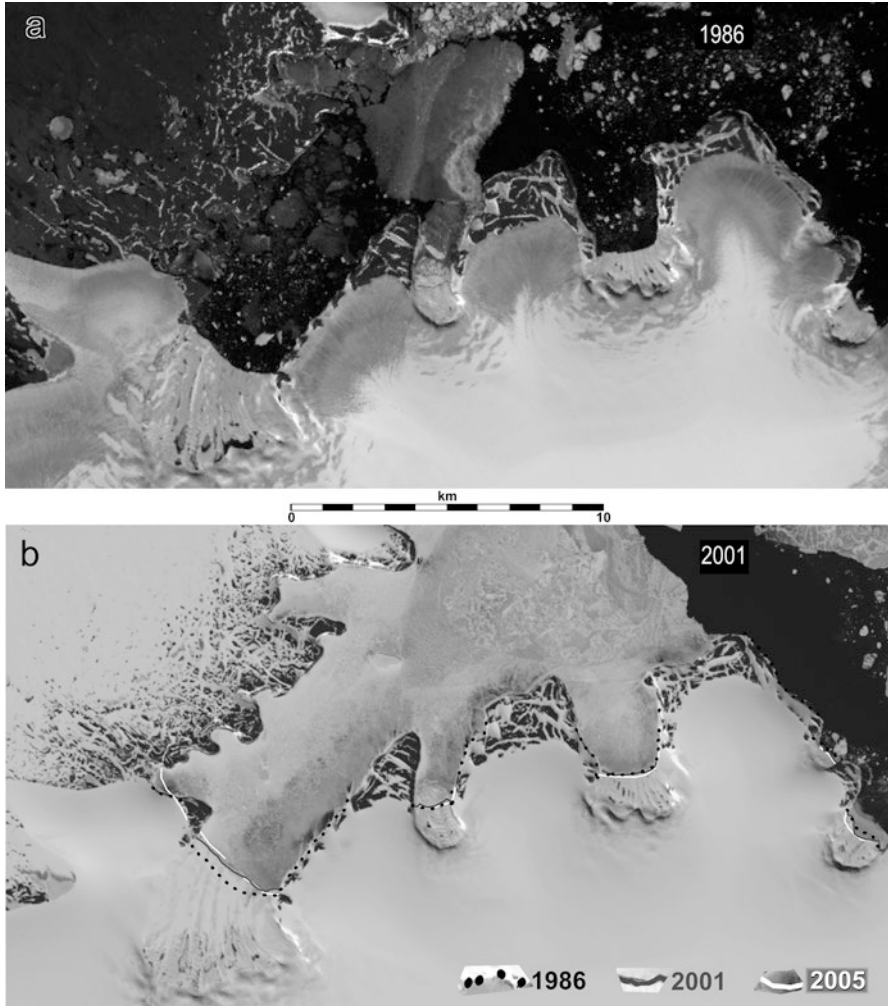
Fig. 3.6 Two satellite images of several areas of possible floating ice shelves in Geographer's Bay, George Land, in the Franz Josef Land archipelago (located in Figs. 3.1c and 3.7). (**a**) 25 July 1986 (Landsat TM image, Path/Row 199/002). (**b**) 17 June 2001 (Landsat ETM+ image, Path/Row 198/002). The ice margins for 1986, 2001 and 2005 are shown

for 315 km² or about 2% of the total area of the ice caps in the archipelago and the largest of these low gradient areas is 45 km² (Fig. 3.7). They make up a total of 175 km or about 7% of the ice-ocean interface from which iceberg calving takes place in the archipelago. Ice surface profiles, derived from analysis of vertical aerial photographs, show slopes of 0.5° on these features, as compared with 3.5–5° on other ice caps in Franz Josef Land (Dowdeswell et al. 2010).
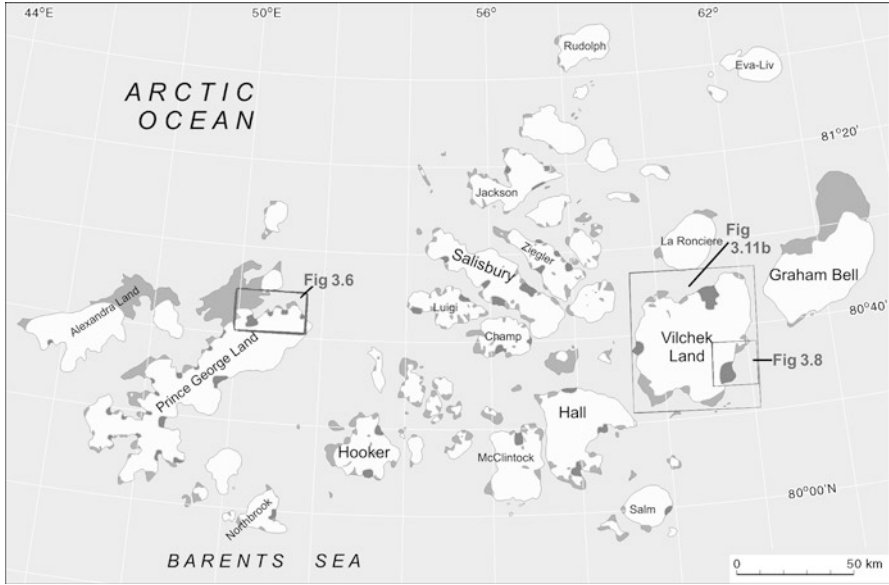
Fig. 3.7 Map of possible floating or nearly buoyant ice in the Franz Josef Land archipelago, shown by dark shading. *Lighter shading* is bare land (Modified from Dowdeswell et al. 1994, Copyright Regents of the University of Colorado)

Two areas of Franz Josef Land with ice inferred to be at or close to full buoyancy are shown in Figs. 3.6 and 3.8. First, the particularly flat areas of ice in five embayments in the deep-water Geographer's Bay on George Land appear likely candidates to be close to hydrostatic equilibrium. Their form is also very like that of the known ice shelves that fill numerous embayments along the coast of the Antarctic Peninsula (Fox and Vaughan 2005). Interestingly, the positions of the margins of these features have remained little altered over the period since 1985, and the largest of the possible shelves has undergone an advance of about 0.5 km over the last 20 years (Fig. 3.6). Secondly, an area of about 30 km^2 at the margin of Zneminity Glacier on Vilczek Land also has a very low-profile surface (Fig. 3.8). This ice margin has retreated by up to 4 km over the past 45 years and continues to produce tabular icebergs up to about 2 km in length.

At least some of the smooth, low gradient features mapped from around the margins of Franz Josef Land ice caps are likely to be floating ice shelves (Fig. 3.7) (Dowdeswell et al. 1994). They have similar ice surface gradients to the known ice shelves on Severnaya Zemlya (Fig. 3.5). There is no requirement for deep water to occur beneath these features, but only that they become buoyant over a significant part of their base. Glacier thinning, due to reduced mass balance since the termination of the Little Ice Age (Dowdeswell 1995; Dowdeswell and Hagen 2004),
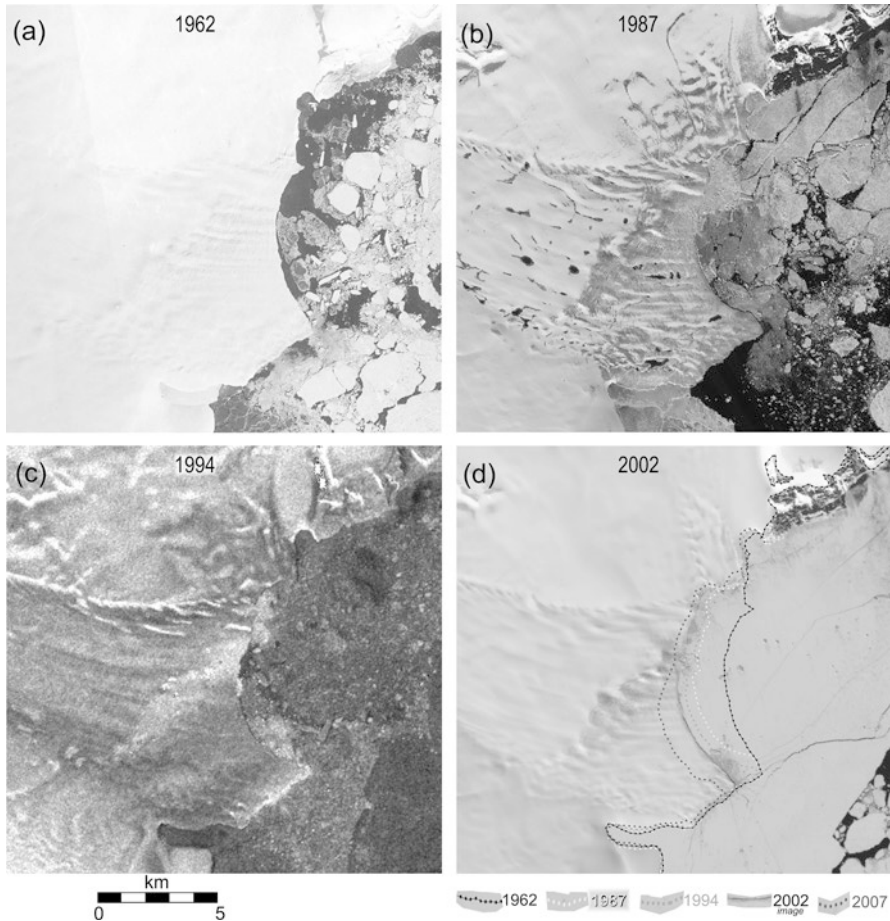
Fig. 3.8 Four satellite images of Znamenity Glacier and the icebergs offshore of Vilczek Land in the Franz Josef Land archipelago. The area is located in Figs. 3.1c and 3.7. (**a**) 18 September 1962 (Declassified Satellite Imagery, DSI). (**b**) 8 August 1987 (Landsat TM image, Path/Row 196/001). (**c**) 22 February 1994 (ERS-1 SAR image). (**d**) 4 June 2002 (Landsat ETM+ image, Path/Row 198/001). Ice margins for 1962, 1987, 1994 2002 and 2007 are shown in **d**, indicating a pattern of consistent ice-margin retreat

may have contributed to the presence of these features. However, an origin for some of these low gradient margins by deformation of an unlithified substrate cannot be ruled out. Irrespective of the basal boundary conditions beneath these features, and of whether individual areas are floating in hydrostatic equilibrium or are merely approaching buoyancy, they provide one of the major modern sources of tabular icebergs to both the eastern Barents Sea and to the Eurasian Basin of the Arctic Ocean (Fig. 3.2b) (Voevodin 1972; Dowdeswell et al. 1994).

3.3.3 Svalbard

Glaciers and ice caps reach the sea along about 860 km of the coastline of the islands of Svalbard (Blaszczyk et al. 2009), but almost none of these marine margins appear to be floating (Dowdeswell 1989) (Fig. 3.2c). This conclusion is reached through several lines of evidence. First, examination of the ice-surface long profiles of many glaciers and ice-cap drainage basins in the archipelago shows none of the very low slopes characteristic of floating ice with a near-zero basal shear stress. These surface-slope data are derived from both airborne radar investigations at megahertz frequencies and the analysis of existing maps (e.g. Dowdeswell 1986). Secondly, basal radar reflections from the marginal parts of many Svalbard ice caps do not show, either qualitatively or quantitatively, the very bright or high-power basal reflectors typical of the ice-water interface at the base of floating ice (e.g. Dowdeswell 1986, 1989; Dowdeswell and Bamber 1995). Thirdly, the icebergs produced from the marine margins of Svalbard glaciers and ice caps are usually small and irregular, rather than the sometimes kilometre-long tabular icebergs characteristic of ice that is floating or close to full buoyancy (Dowdeswell 1989). Fourthly, comparison of offshore bathymetry and radar-derived marginal ice thickness, where both are available, shows values that are similar within the limits of the errors in each method.

There may be short periods, during the active phase of a surge cycle as some outlet glaciers advance into deepening water, when marine margins may become floating prior to subsequent retreat through iceberg calving. Photographic evidence from the margins of Negribreen in eastern Spitsbergen shows the presence of tabular icebergs during the early 1980s (Fig. 3.2d), which may be indicative of short term floatation. However, such phenomena are likely to be transient and unrepresentative of the generally grounded tidewater margins of Svalbard ice masses. In addition, there are few measurements of the transient ice thickness or surface slope during the active phase of surging (e.g. Liestøl 1973).

3.3.4 Novaya Zemlya

Similarly to Svalbard, there is little evidence that the margins of the marine-terminating glaciers on Novaya Zemlya are floating. Most glaciers are retreating and thinning at present and it is noted that retreat into deepening water may induce short-term floatation and rapid calving at the terminus (Moholdt et al. 2012a; Carr et al. 2014). Several of the larger outlet glaciers are known to be of surge-type (Dowdeswell and Williams 1997; Grant et al. 2009). In such cases, short-term floatation during surge advance into deep water cannot be ruled out, but the marine margins of the ice caps on Novaya Zemlya appear typically to be grounded tidewater glaciers.

3.4 Icebergs Derived from Eurasian Arctic Ice Masses

Floating and grounded ice margins in the Eurasian Arctic tend to produce icebergs of rather different dimensions (Figs. 3.2, 3.9). Icebergs produced from floating ice shelves are characteristically tabular in plan, with a surface that is initially flat, reflecting the often smooth and low-elevation ice shelves from which they are calved (Fig. 3.9a). Willis et al. (2015) report tabular icebergs with a calculated thickness of about 120 m produced during the 2012 breakup of Matusevich Ice Shelf in Severnaya Zemlya.

The size-frequency distribution of tabular icebergs in the Barents Sea, produced from the margins of Franz Josef Land ice caps, is shown in Fig. 3.10b (Voevodin 1972). The largest tabular icebergs are several kilometres in diameter. Icebergs of similar size have been observed close to the margin of Znemenity Glacier, one of the largest single drainage basins in the archipelago at about 400 km^2, where the very low ice-surface slope suggests that the margin is at or close to full buoyancy (Dowdeswell et al. 1994). Icebergs of up to about a kilometre in maximum length can be seen in several of the satellite images comprising Fig. 3.8. Other reports and analyses of icebergs derived from the Russian Arctic islands include Zubin et al. (2005) and Kubyshkin et al. (2006).

By contrast, icebergs derived from tidewater ice margins, grounded below sea level, are usually much smaller and more irregular in shape than those produced from ice shelves (Fig. 3.9b). Their morphology is often restricted by the spacing of crevasses close to the margin, where the ice is usually in longitudinal tension (Hodgkins and Dowdeswell 1994). Individual icebergs are usually tens to about one hundred metres in diameter when calved. The size-frequency distribution of icebergs derived from the fast-flowing glacier, Kongsvegen, in north-western Svalbard is shown in Fig. 3.10a (Dowdeswell and Forsberg 1992). In this fjord, icebergs are usually irregular in shape and less than about 20 m in diameter, and are seldom greater than 100 m across.

3.5 Retreating Marine Ice-Cap Margins and Their Sensitivity

The greatest volumes of ice in the Eurasian Arctic are held in a number of large ice caps, each of several 1000 km^2 in area; the largest are Austfonna in eastern Svalbard (area 8000 km^2, volume 2500 km^3), Academy of Sciences Ice Cap in Severnaya Zemlya (area 5500 km^2, volume 2200 km^3) and the Vilczek Land Ice Cap in Franz Josef Land (area 1840 km^2, volume 340 km^3). At present, many of these ice caps have extensive marine margins, although ice shelves are rare or absent. Mass is lost, therefore, by both surface melting and iceberg production, with iceberg loss accounting for about 30–40% of total mass loss (Dowdeswell et al. 2002, 2008). Most of these ice caps are undergoing retreat and thinning (e.g. Moholdt et al. 2012a).
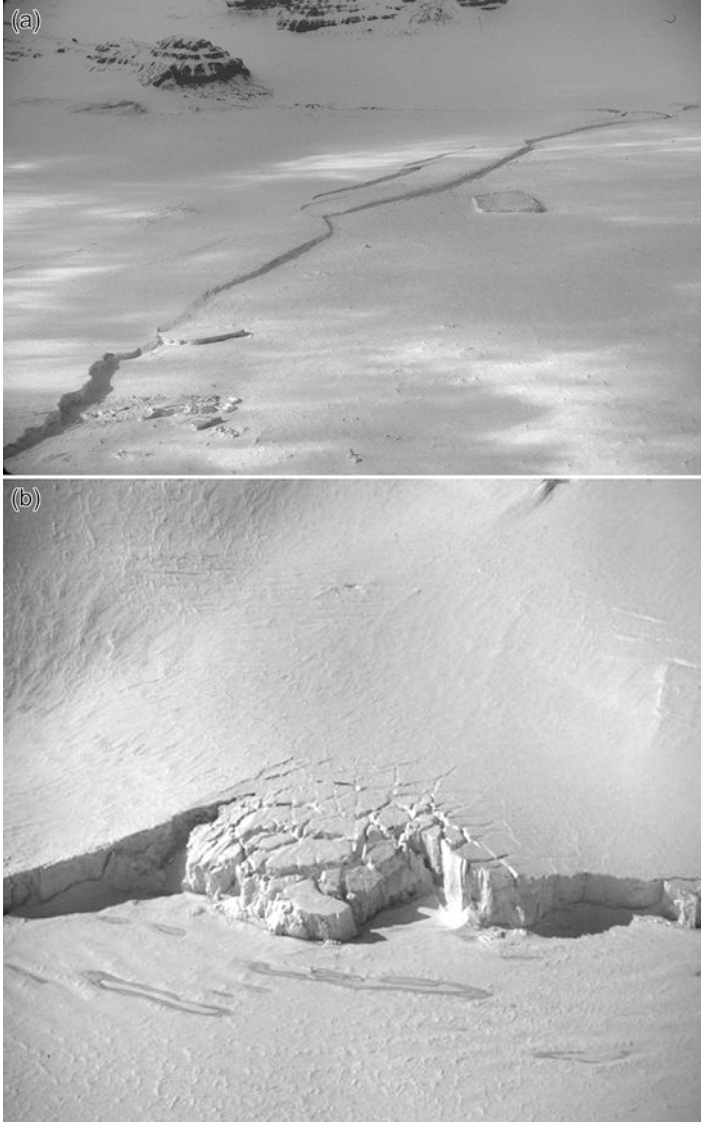
Fig. 3.9 Images of icebergs calved from floating and grounding ice margins in the Eurasian Arctic (Photographs: J.A. Dowdeswell). (**a**) Tabular icebergs from the very flat marine margin of a glacier on Franz Josef Land, May 1994. The low-gradient ice-surface profile indicates that the margin is at or close to full buoyancy. Note the fracture suggesting that a long but rather narrow iceberg of almost a kilometre in maximum dimension is about to be calved. (**b**) The crevassed margin of a small grounded tidewater glacier on George Land in Franz Josef Land, May 1994. Icebergs of irregular shape and maximum dimension about 100 m across are about to be calved from the ice margin, with release taking place when the winter sea-ice cover in the photograph breaks up
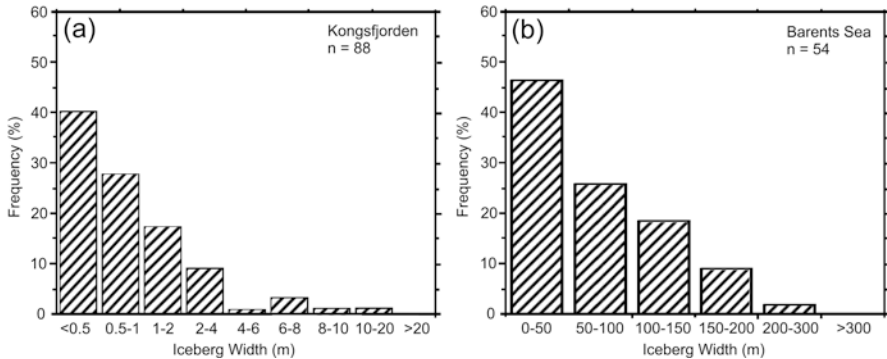
Fig. 3.10 Size-frequency distributions of the width of icebergs calved from grounded and floating ice margins, respectively, in the Eurasian Arctic. (**a**) Icebergs of irregular shape in Kongsfjorden, north-west Svalbard (*Source*: Dowdeswell and Forsberg 1992). (**b**) Tabular icebergs observed in the Barents Sea (*Source*: Voevodin 1972)

The sensitivity of these ice caps to atmospheric and ocean warming over the coming century, where mean annual temperature rise is predicted to be 3–6°C or even more for the Arctic depending on which predictive scenario is used (IPCC 2013), will be influenced in part by the proportions of their beds that are located below present sea level and whether or not they are floating. For tidewater ice masses in general, the mechanisms and pattern of retreat are likely to be complex, involving both thinning and buoyancy effects linked to bed geometry; retreat is unlikely to be a simple linear function of temperature change. In Greenland, the penetration of warmer waters into a number of fjords in the past few years has resulted in enhanced basal melting, thinning and breakup of several floating ice tongues at the margins of fast-flowing outlet glaciers (e.g. Holland et al. 2008; Nick et al. 2009; Christoffersen et al. 2011). Although little is known about changing water-mass temperatures around the Russian Arctic islands, a similar mechanism could in principle lead to the rapid thinning and breakup of floating ice shelves on Franz Josef Land and the Matusevich Ice Shelf on Severnaya Zemlya. In the longer term, the retreat of tidewater ice margins onto land will mean that iceberg production and marine melting cease. Further mass loss would, therefore, be by surface melting and runoff alone, providing a natural constraint on the rate of subsequent decay. A similar argument on sensitivity to warming would, of course, apply to the large marine-terminating outlet glaciers draining, for example, the upland icefields of Spitsbergen and Novaya Zemlya; ice-penetrating radar data exist for only some of these glaciers.

The bed topography of the three largest ice caps in the Eurasian Arctic, derived from ice-penetrating radar studies, shows that significant areas of each ice cap lie below sea level (Fig. 3.11). The elevation of the bed of Austfonna is shown in Fig. 3.11c. About 28% of the bed lies below present sea level (Dowdeswell et al. 2008). The marginal ice thickness often exceeds 100 m and the minimum ice thickness is about 85 m. About 50% of the bed of the Academy of Sciences Ice Cap is below present sea level (Fig. 3.11a), and long profiles of the ice cap show that parts
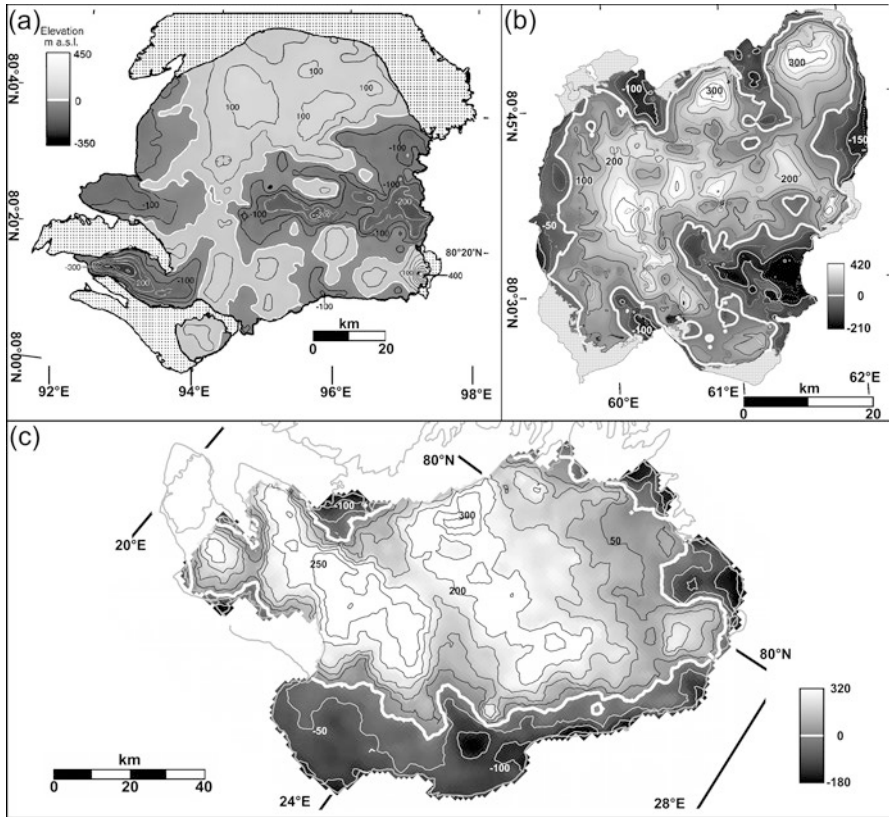
Fig. 3.11 Bed topography of three large ice caps in the Eurasian Arctic, showing the proportions above and below present sea level. (**a**) Academy of Sciences Ice Cap, Severnaya Zemlya, located in Fig. 3.1d (Data from Dowdeswell et al. 2002). (**b**) Vilczek Land Ice Cap, Franz Josef Land, located in Figs. 3.1c and 3.7. (**c**) Austfonna, Nordaustlandet, Svalbard, located in Fig. 3.1b (Data from Dowdeswell 1986; Dowdeswell et al. 2008)

of its bed lie below sea level over 40 km inland of the ice margin (Dowdeswell et al. 2002). The minimum bed-elevation is −207 m on the eastern side of the ice cap, and about −317 m in the south-west. The northern part of the ice cap is, by contrast, underlain by a relatively smooth topography that is above modern sea level. The ice cap on Vilczek Land has about 25% of its bed below present sea level and a maximum below water bed-elevation of about −200 m (Fig. 3.11b).

In each of these ice caps, the lowest elevation areas of the bed are close to the present ice margins. Thus, ice will usually retreat into shallower water, making the likelihood of the development of floating ice margins and rapid iceberg production low, although any atmospheric warming will still enhance the rate of mass loss due to surface melting. This bed-topographic situation contrasts with that in much of West Antarctica, where the ice-sheet bed becomes deeper with distance inland due to long-term isostatic loading by ice several kilometres in thickness (e.g. Anderson 1999).

Taking the case of the largest ice cap in the Eurasian Arctic, Austfonna (Fig. 3.11c), its overall calving loss has been calculated at between about 1.3 and 2.5 km^3 year^{-1} (Dowdeswell et al. 2008; Moholdt et al. 2010). Given that Austfonna has a volume of about 2500 km^3, a simple calculation demonstrates that, if this rate of loss continued, the ice cap could disappear within about 1000 years. However, this is a pessimistic view even in a warming Arctic, since the bed elevation of Austfonna shows that less than 30% of its area lies below sea level (Fig. 3.11c). Thus, retreat of the ice margin onto land would immediately halt the component of mass loss through iceberg calving and, hence, slow the rate of decay; warming would, nonetheless, continue to enhance the rate of mass loss due to surface melting. Much of bed topography beneath the Academy of Sciences and Vilczek Land ice caps also lies close to or above sea level (Fig. 3.11a, b), suggesting that there is a natural break on the rapid collapse of these ice caps through floatation and rapid iceberg production.

3.6 Conclusions

- Despite the presence of about 4000 km of marine-terminating glaciers and ice caps in the Eurasian Arctic (Fig. 3.1) (Sharov 2005), there are few areas of floating ice shelves. Neither are there extensive areas of multi-year shorefast sea ice, which might slow iceberg calving and, indeed, thicken into composite ice shelves themselves.
- The Russian Arctic archipelagos of Severnaya Zemlya and Franz Josef Land appear to contain some ice shelves in addition to grounded tidewater ice fronts (Fig. 3.2a, b). The largest ice shelf was the Eurasian Arctic is the Matusevich Ice Shelf, Severnaya Zemlya, with an area of about 240 km^2, fed from drainage basins totaling about 1100 km^2 (Figs. 3.3, 3.4) (Williams and Dowdeswell 2001). This ice shelf largely broke up in 2012 (Willis et al. 2015)
- In Franz Josef Land, a number of ice caps have smooth and very low surface gradients at their seaward margins, covering over 300 km^2 or about 2% of the total area of the ice caps in the archipelago (Fig. 3.7) (Dowdeswell et al. 1994). They are located mainly in relatively protected embayments (Fig. 3.6), and produce large tabular icebergs (Fig. 3.9a). Whether individual areas are floating in hydrostatic equilibrium or are merely approaching buoyancy, they provide the major modern source of tabular icebergs to the Barents Sea (Fig. 3.10b).
- Although Svalbard has about 860 km of coastal ice cliffs, almost none of the ice margin appears to be afloat (Dowdeswell 1989) (Fig. 3.2c). There may be short periods, during the active phase of the surge cycle, where marine margins become afloat prior to retreat through iceberg calving. Neither is there evidence that the margins of the marine-terminating glaciers on Novaya Zemlya are floating.
- 25–50% of the bed of the three largest ice caps in the Eurasian Arctic lies below sea level (Fig. 3.11). Thus, in a warming Arctic, the ice margin would eventually retreat onto land, curtailing mass loss by iceberg production and providing a break on rapid ice-cap disintegration through calving (Dowdeswell et al. 2008).

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