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Reflections on subglacial megafloods: their possible cause, occurrence, and consequence for the global climate

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Abstract

Huge water reservoirs exist subglacially, for instance in the form of lakes. Failure of a wall around such a lake underneath the central part of a large ice mass may result in huge water outbursts. The resulting megafloods will rarely be traceable along the ice front, because much power is lost by friction and because the flood spreads subglacially over a large area. Truly giant meltwater outbursts might, however, still have an enormous power when reaching the marginal area of an ice cap. Such a megaflood may both affect the integrity of the ice mass, and help create a sliding layer over which huge ice masses can be easily transported towards the ocean, thus triggering a Heinrich-like event. This would have great impact on the global climate. Some of the Heinrich events that occurred during the past hundreds of thousands of years may well have been due to giant subglacial water outbursts, and such a situation may equally well occur in the time to come.

Keywords: jökulhlaups, megafloods, Heinrich events, sliding layer, subglacial lakes, climate change

Introduction

Some of the potentially more catastrophic natural phenomena are the sudden outbursts of glacial meltwater (Fig. 1), commonly called 'jökulhlaups' (from the Icelandic 'jökul' = glacier; and 'hlaup' = run-off). Most of the 'classical' Icelandic jökulhlaups seem directly related to geothermal heating or subglacial volcanism (see, among others, Kjartansson, 1951; Tryggvason, 1960; Björnsson and Einarsson, 1991; Larsen et al., 1998; Björnsson et al., 2000; Larsen, 2000; Maria et al., 2000). Volcanism-induced subglacial melting outside Iceland has been desribed from the Azas Plateau in the Tuva Republic of the Russian Federation (Komatsu et al., 2007). The term 'jökulhlaup' is also used for sudden meltwater floods (with a discharge many times larger than normally) that have a different origin, for instance the failure of an ice or rock mass damming off a supraglacial or proglacial lake (Kochel et al., 2009).

Although the term 'jökulhlaup' is commonly used for the floods that are released in front of the ice (and thus can be observed directly), the term has also been used for supraglacial examples (Russell et al., 2001b). Although referring to a principally identical feature, the term will – in order to avoid confusion – not be used in the present contribution for the uncommonly large floods inside or underneath an ice cap that might originate due to the sud-

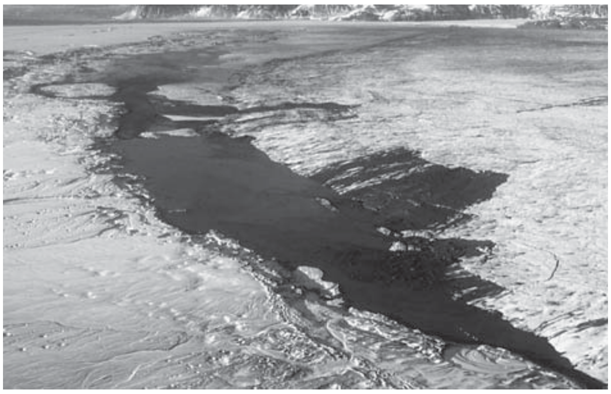

Fig. 1. The Skeiðarárjökull jökulhlaup following the Gygja river, which is here ~100 m wide. The picture was taken on 5 November 1996 at 12.00 h, about one hour after water started to emerge from this part of the Vatnajökull glacier.

den release of huge volumes of meltwater from an englacial or subglacial water mass. Instead, the terms 'subglacial outburst' and 'subglacial megaflood' will be used.

Most Icelandic jökulhlaups cause little damage or casualties, because they involve a moderate mass of water, and occur in areas with little population. Their economic consequences can nevertheless be large (Rist, 1983; Jónsson et al., 1998), as the floods may destroy roads and bridges (Fig. 2). The damaging nature is partly due to the torrential character of the floods, which commonly carry a huge amount of cobbles and boulders. These may be transported through relatively narrow, but deep channels

Fig. 2. The destructive power of the 1996 Vatnajökull jökulhlaup. **A:** On 5 November 1996 at 14.40 h. The 900 m long Skeiðará bridge and protective dike system over the river are still intact, in spite of the high discharge of 15,000 $m^3 s^{-1}$. **B:** The discharge (about 5,000 $m^3 s^{-1}$ at this time, a few hours after the situation shown in Figure 2-A) has diminished, but the eastern end of the bridge crossing the streamway over the sandur plain has been washed away in the meantime.

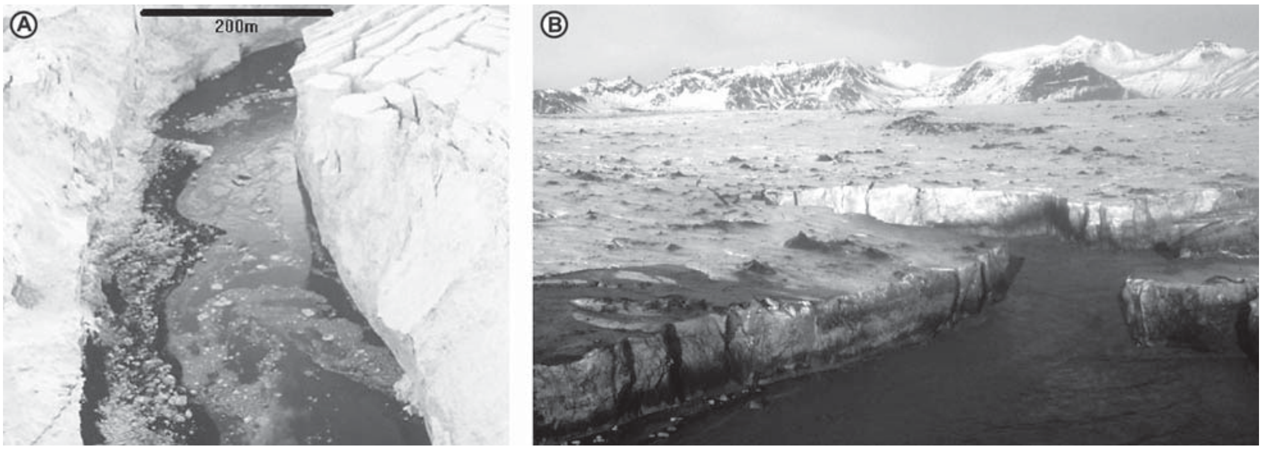

Fig. 3. Deep channels within the snout of the Vatnajökull glacier during the 1996 jökulhlaup. **A:** During the main phase (photo Magnus Haldorsson). **B:** During the waning stage.

(Marren et al., 2009), which can be considered as the proglacial succession of the subglacial channels that become visible in the distal parts of the ice mass as a result of hydraulic fracturing of the snout (Fig. 3). Jökulhlaups can change both proglacial landforms (Smith et al., 2000; Russell et al., 2001a; Fay, 2002b) and proglacial sedimentation patterns (Maizels, 1991; Russell, 1993; Russell et al., 1999a; Fay, 2002a; Fleisher et al., 2003).

It is commonly accepted that jökulhlaups greatly contribute to the accumulation of sandurs (Tómasson, 1974; Maizels, 1983, 1989, 1993, 1997; Russell & Knudsen, 1999b, 2002b; Cassidy et al., 2003) because huge volumes of sediment are transported (Tómasson et al., 1980) – and the large sediment load influences, in turn, the jökulhlaup mechanism (Fowler & Ng, 1996). Yet, the deposits that are formed by a meltwater outburst inside an ice mass, i.e. by the failure of an ice dam blocking an englacial lake (Roberts et al., 2000a), as well as those formed underneath the ice by the outburst from a subglacial lake or by the sudden melting of large ice masses due to volcanic activity underneath the ice cap (Russell et al., 2003; Stevenson et al., 2009) are rarely preserved, because they are often destroyed by later meltwater outbursts. Even from outwash areas in front of the ice, descriptions of jökulhlaup deposits are commonly brief (Calkin, 2002). Only few descriptions of catastrophic floods of this specific type regard the Pleistocene (among others by O'Connor & Baker, 1992; Smith & Fisher, 1993; Rudoy & Baker, 1993; Geirsdóttir et al., 2000; Mokhtari Fard & Ringberg, 2001; Rudoy, 2002). Large floods of meltwater from other sources (e.g. those from Lake Agassiz, released by the retreat of the Laurentide Ice Sheet that had blocked the outlet) have been reconstructed in fairly much detail (see, for instance, Teller et al., 2002; Clarke et al., 2004; Clayton & Knox, 2008). Such supraglacial and proglacial meltwater floods are out of scope in the present contribution.

Large meltwater outburst derived from the subglacial release of huge water masses are known in fairly much detail only from the 20th century (Guðmundsson et al., 1995), but reconstructions have also been made for Pleistocene occurrences. It was found, for instance, that broad, deep tunnel valleys along the margins of some lobes of the Laurentide Ice Sheet were formed by headward erosion of conduits through which catastrophic releases of water from subglacial reservoirs could take place, and that these reservoirs needed only a few decades to become refilled (Hooke & Jennings, 2006).

Well known jökulhlaups

The best known proglacial (subaerial) jökulhlaups are the small- and medium-scale events that occur on average every 1–2 years on Iceland. Much information is available with respect to their discharge and sediment load (Tómasson, 1974; Tómasson et al., 1980). These small-scale events commonly take place more

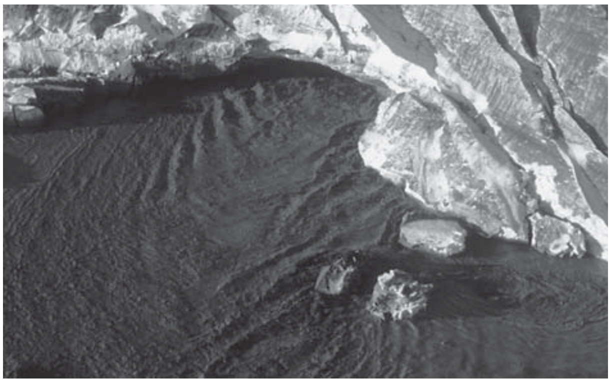

Fig. 4. Water emerging from underneath the front of the glacier on November 5, 1996, after the eruption of the Gjálp. Main portal, formed by fracturing of the snout of the Skeiðarárjökull, during the waning stage, one day after the jökulhlaup started. The ice wall is almost a hundred metres high.

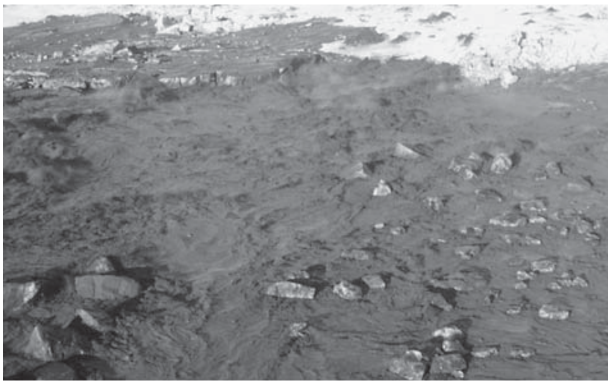

Fig. 5. Large ice blocks (some tens of metres in diameter) were carried along with the water loaded also with smaller debris, during the first day of the Skeiðarárjökull outburst.

or less periodically (Mathews & Clague, 1993). The periodical occurrence can be due to the seasonal shift of glacier fronts, damming off glacial lakes during advance, and providing an outlet again during retreat (Tweed & Russell, 1999).

In contrast, large-scale jökulhlaups tend to occur with irregular intervals or as isolated phenomena (Brodzikowski & Van Loon, 1987, 1991), due to the destruction of lake-ice masses damming off a meltwater lake; the destruction of such ice dams is commonly ascribed to melting due to a sudden increase of geothermal heat (cf. Björnsson & Guðmundsson, 1993), related to volcanic eruptions. In other cases, it turns out that subglacial tunnels are formed that house water flows which undermine – by physical or thermal erosion – an ice mass that dams off a lake (Thórarinsson, 1953; Liestöl, 1956; Björnsson, 1974; Nye, 1976), thus initiating a sudden outburst (Liu-Jinshi, 1992; Zhang-Xiangsong, 1992).

The characteristics of these large-scale jökulhlaups are much less well known than those of their smaller counterparts because the frequency of such events diminishes roughly exponentially with increasing size, as do most natural events. The best known examples of large-scale jökulhlaups (floods with discharges of at least tens of thousands of cubic meters per second) are those of 1918 (Katla) (Thórarinsson, 1957; Björnsson, 1974; Björnsson et al., 2001) and 1996 (Vatnajökull) (Jónsson et al., 1998; Russell and Knudsen, 1999a, 2002a; Gomez et al., 2000, 2002). The latter, which lasted 33 hours, was caused by the rapid melting of some 3.8 km^3 of ice (Guðmundsson et al., 1997; Björnsson, 2002) due to a volcanic eruption on 30 September 1996 underneath the Vatnajökull ice cap (Guðmundsson et al., 1997). It resulted in a sudden flood of some 45,000–53,000 m^3 of water per second that was issued from underneath the glacier (Fig. 4) at velocities up to 6 m s^{-1}, and transported ice blocks (Fig. 5) of at least 25 m long over the Skeiðararsandur. This flood was nevertheless small compared to the 1918 Katla jökulhlaup, a torrential flood of some 300,000 m^3 s^{-1} of water, transporting 25,000 tons of ice per second and an equal amount of sediment, which resulted in a density of 1.170 g cm^{-3} (Tómasson, 1996). Krüger (1994) mentions the transport of ice blocks of 40–50 m (most of which were left behind on the sandur area between the ice front and the sea) by this flood. The largest Holocene jökulhlaup known from Iceland had a peak discharge of 900,000 m^3 s^{-1} (Alho et al., 2005). This catastrophic event was still of restricted size, in its turn, in comparison with a jökulhlaup that took place in front of Lake Missoula during the late Pleistocene, estimated to have reached a peak discharge of at least 17 ($\pm$3) million m^3 s^{-1} (O'Connor & Baker, 1992).

Objectives

The above can be considered as a simplified overview of some aspects of jökulhlaups that are relevant in the framework of questions such as: (1) is it possible that only part of the subglacial outbursts can be observed directly, because most of the meltwater remains hidden due to an entirely subglacial development (water running from one subglacial reservoir to another); (2) could such subglacial meltwater outbursts have extreme characteristics; and (3) if so, might the effects spread to beyond the ice front, and what could be the effects for the non-glaciated world (for instance, for the global climate)?

It seems worth while to consider these questions, as a good understanding of large meltwater floods may be beneficial for economic, safety and climate-policy reasons. Modelling on the basis of a better insight may help to predict such floods (Clarke, 1982; Björnsson, 1992; Maizels and Russell, 1992) and thus to reduce the risk of damage and loss of lives.

It seems also worth while to mention here explicitly that the main objective of the present contribution is to discuss the possibility of the occurrence of huge subglacial water outbursts, the possible sequence of events, and their possible consequences. It is not intended to analyse the possible pertinent processes themselves in any detail; nor is it intended to analyse the hydrological conditions or the physics that play a role just before, during and immediately after such an event, as no measurements of the physical conditions during such an event have ever been made under the central part of a huge ice cap; such an analysis could therefore now not been based on measurement data. Rather it is the intention to stimulate other researchers to think about methods that might help to gather such data, and to discuss the possible causes and consequences of huge subglacial water outbursts.

Considerations

If extremely large subglacial outbursts might occur, huge bodies of subglacial water are a prerequisite. Large ice bodies tend to have – at least locally – a temperate character, which means that the combination of the geothermal heat flux and the insulation capacity of the ice results in the presence of water at the base of the ice mass. The volume of water can, indeed, be extremely large: Lake Vostok, under 3750–4150 m of ice of the Antarctic ice sheet (Souchez et al., 2003), has a surface area of some 14,000 km^2 (roughly 200×70 km). With a maximum depth of 670 m (Priscu et al., 1999), the water content of the lake is some 5,000 km^3. This does not necessarily imply, however, that all this water – or a significant part of it – may be released in the form of a giant subglacial flood, but even a minor percentage of such a water volume could easily result in a sudden flood that may be comparable with those described from glacial times. Such an event requires, obviously, specific conditions, among which changes in the configuration of the ice masses that surround the lake, or susceptibility of the surrounding hard-rock walls to erosion.

Lake Vostok (Fig. 6) was, for several reasons, the object of much research during the past decade. It was found, for instance, that melting and freezing of the roof above the lake involve considerable quantities of ice (Jouzel et al., 1999; Siegert et al., 2000), which may be related to the heat flux from the lake into the ice (Thoma et al., 2008). Keeping in mind that there are more than 150 subglacial lakes in the Antarctic region (Kohler, 2007), although not of the same size, one must conclude that the total mass of material that undergoes phase

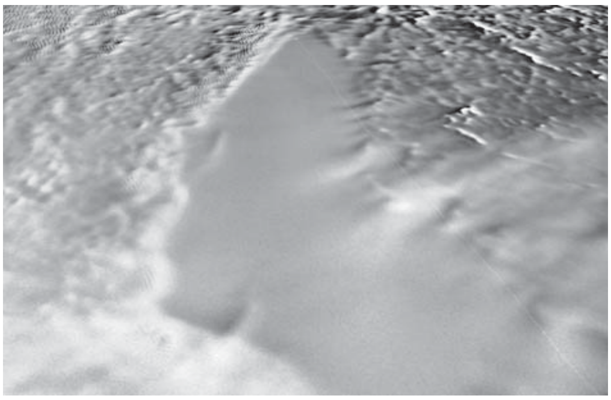

Fig. 6. Subglacial Lake Vostok (~200 km×70 km) on Antarctica, made visible through RADARSAT. Photo NASA/Goddard Space Flight Center Scientific Visualization Studio.

changes between water and ice must be much larger than the figures for Lake Vostok alone indicate. This is important because it implies that there are giant amounts of water available under the Antarctic ice sheet, which might be the source of sudden subglacial outbursts, for instance when the ice mass damming off such a lake melts away or is otherwise affected, for instance being moved, as may be the case when an ice-flow changes its direction.

The interest in Lake Vostok and other subglacial lakes has not yet answered all questions, partly because a drilling project was stopped in order to avoid contamination of a possible 'fossil' fauna or flora with present-day organisms (Nadis, 1999). Little information is therefore available about such aspects as (1) the amount of ice melting annually; (2) the mass balance of melting ice and freezing water; (3) the conditions limiting the size of the lake (ice dams? hard-rock topography?); (4) the characteristics (direction, transfer velocity, etc.) of the geothermal heat flux; (5) the movement of the ice immediately surrounding the lake, possibly temporarily blocking the outflow and eventually losing its function as a barrier again. It has been predicted already in 2000 that, in due time, Lake Vostok (or any other huge lake under the ice mass of Antarctica) might become the source of a giant subglacial meltwater outburst (Van Loon, 2000), and this prediction has since been proven to be correct, because a water mass of some 2 km^3 travelled between 1996 and 1998 through the Adventure Subglacial Trench on Antarctica from one subglacial lake to another (Wingham et al., 2006; Carter et al., 2009).

The finding that huge water masses flow from one subglacial lake to another proves once more that the hydrology under large ice caps is still poorly understood (Wingham et al., 2006). It also proves that some ideas that are commonly taken for granted, commonly on the basis of physics that apparently do not prevail, are incorrect. It is often assumed, for instance, that – in the central parts of a large ice mass – no significant air-filled space can be present between the substratum and the ice, because of the downward pressure exerted by the weight of the ice. It is also commonly assumed that no such space can be present between the water surface of a subglacial lake and the ice mass, because the "potentiometric surface is high up in the ice, just as in any confined groundwater aquifer". If no such air-filled spaces between the water surface and the ice would exist, it can, however, not be explained why huge water masses can embouch in a subglacial lake. Moreover, one might question how 'lake ice' can be formed if the water is under high pressure, and if there is no space for a volume increase. It is therefore, in contrast to common statements, not realistic to exclude by definition that large subglacial spaces occur through which megafloods can find their way.

Sequence of events characterising a giant subglacial outburst

Excellent progress has been made toward a refined theory of floodwater flow through glaciers (see, among others, Clarke, 2003), but the insight into the occurrence of outbursts and related processes under subglacial conditions is still small in comparison to the insight into proglacial flows: only two cases of floods from one subglacial site to another are well-known. The first is the 1996 Gjálp eruption in Iceland, where the meltwater from the eruption site accumulated in Grímsvötn Lake for several weeks before being released as a jökulhlaup that reached the area in front of the ice (Guðmundsson et al., 1997); it is known that the water volume of this lake can fluctuate considerably: in the days between 11 and 16 August 2004, it increased by 18 million cubic metres (Berthier et al., 2006). The second example regards the above-mentioned example in Antarctica, where a large subglacial water flow made the water level in one subglacial lake drop, and in another rise (Wingham et al., 2006). Differences in topographic height of the places between which the water flows can explain such transport, but differences in hydrostatic pressure may also play an important part.

There is clear sedimentary and geomorphological evidence from retreating ice margins and formerly glaciated areas for subglacial floods (see, among others, Russell, 1994): the glaciological effect of floodwater movement through glaciers is reflected in ice fracturing and ice-surface sagging in the inlet region for the subglacial flood tract (Sturm and Benson, 1985). Hydrodynamical theories on the propagation and growth of subglacial floods have been obtained from observations in the inlet and outlet zones of flood-affected glaciers (Clarke, 2003). It seems therefore likely that huge lake outbursts, resulting in much larger floods than ever witnessed for subaerial jökulhlaups in historical times or reconstructed for prehistorical times, can occur underneath large ice masses. Only the following sequence of events need take place for the purpose:

1. Due to volcanic activity (Fig. 7), a temporarily increasing geothermal heat flux, or the supply through crevasses and tunnels of initially supraglacial meltwater, large water bodies are formed underneath a thick ice mass. Such water reservoirs may also develop in zones of equipotential convergence, at the point where hydraulic gradients are minimal. Ever growing lakes may thus originate, the final extent of which is determined by either a 'high' in the hardrock substratum or an ice dam.
2. The water level rises as long as sufficient heat – from a volcanic eruption or from the geothermal heat flux – is supplied for additional melting of ice, or as long as additional water is supplied through upstream channels or through crevasses. This process goes on as long as the bordering ice mass or hard-rock 'high' is higher than the water level (this may last thousands of years).
3. The water level reaches the lowest upper limit of a hardrock barrier and starts overflowing, or the water pressure in the lake becomes high enough to force a water flow out of the lake by forming a tunnel underneath an ice dam or by flotation of such a dam (Tweed, 2000).
4. The result is, particularly in the case of an ice barrier, a rapid downwards erosion of the dam, resulting in an equally rapidly increasing release of a water mass with similarly increasing erosional power, so that a megaflood follows, which has all characteristics of a jökulhlaup (cf. Walder & Costa, 1996).
5. The process stops after a situation has been reached that either the lake has been emptied, or no further downwards erosion of the barrier takes place.

Fig. 7. Eruption of the Grímsvötn volcano under the Vatnajökull glacier. Photo Oddur Sigurdsson.

After this sequence of events has occurred, a new ice dam may eventually form and a new, similar sequence of events can start.

If sufficient air-filled space is available underneath the ice mass (and spaces must be available underneath temperate ice masses due to ice melting as a result of the geothermal heat flux in combination with the insulation capacity of ice), and if the distance to the ice front is sufficiently large, the torrential flood will gradually loose its power (by friction and by spreading over a large area) so that it need not necessarily preserve its torrential character when the water reaches the area in front of the ice. In such a case, the outburst will remain unnoticed: only an insignificant temporary increase of the sediment-loaded meltwater flow will possibly be recorded, contributing to the buildup of 'normal' glaciofluvial deposits and glaciolacustrine sediments (Gruszka, 2005).

Possible consequences

It is known from the Antarctic and Greenland ice sheets and many small glaciers that subglacial water can act as a lubricant, forming a 'film' over which ice masses can slide easily

(Björnsson, 1998). It should be emphasised in this context that such sliding is a process that differs fundamentally from the transport of, for instance, icebergs by ocean currents. In the latter case, buoyancy allows the water to carry the ice masses, whereas it is the almost negligible friction that allows an ice mass to slide downwards over the lubricant (sliding) layer. As a consequence, ice masses with considerable height can slide down over the lubricant water layer, also when the thickness of this layer is by far insufficient to allow such large ice masses to float within the water layer.

In addition, it is assumed on the basis of 'fossil' deposits that fairly strong subglacial meltwater streams can transport a large amount of clastic particles, thus forming low-viscosity slurries (Knight, 2003); such slurries may increase the effectiveness of the lubricant (sliding) layer underneath an ice mass. In the vicinity of the ice front, a water layer may therefore facilitate the start of surges, resulting in ice masses that move relatively fast over the sliding layer in a downslope direction (a slope of only a fraction of 1° is sufficient). Large icebergs can thus be transported to the ocean. The ice masses that slide down over the water layer can originate because more or less vertical fractures (crevasses) can be formed in the ice (Malthe-Sørenssen et al., 1998; Waller et al., 2001), due to tensile stresses induced by the ice flow. Particularly lifting of ice by flowing water masses creates large tensile stresses and rupturing of the ice, which explains why large ice blocks can be transported by high-magnitude jökulhlaups. Shock waves may also play a (probably minor) role in the formation of ice blocks that can be transported over a lubricant layer. Such shock waves can arise from the sudden pressure exerted on ice walls if torrential floods find these walls on their ways.

It is obvious that the thickness (which influences the effectiveness) of a lubricant sheet of water depends on the amount of water supplied. Considering that increasingly larger floods can break up ever thicker ice masses, there must be a positive relationship between the force of a subglacial megaflood (and thus its mass) and the distance from the ice front where cracks may be formed that isolate ice masses that may start sliding down over the lubricant water sheet. Large floods themselves may, moreover, favour the development of fractures in the ice (Russell et al., 1999b; Roberts et al., 2000b).

The above reasoning (Van Loon, 2000) comes – though following an entirely different approach – to a similar conclusion as reached by Johnson & Lauritzen (1995). They explain the global cooling of 116 ka ago as the result of a Heinrich event. The Heinrich event of 116 ka ago (reflected by a layer of dropstones in the Atlantic; see Scourse et al., 2000) occurred according to Johnson & Lauritzen (1995) as a consequence of a giant jökulhlaup. This flood must have originated after an ice dam that was formed due to surging and that was responsible for the presence of Lake Zissaga had failed; Lake Zissaga, with its 2,900,000 km^2 surface area and its 600,000 km^3 water content, was 150 times larger than Lake Agassiz, which can be considered as its successor lake, covering only part of the Lake Zissaga area. The fundamental difference between the idea of Johnson & Lauritzen (1995) and the hypothesis presented here is that they reconstruct, like Teller et al. (2002) and Clarke et al. (2004), a jökulhlaup derived from a subaerial lake to explain climatic cooling (by triggering a Heinrich event); in contrast, the present contribution deals with the possibility of large subglacial lakes as the source of megafloods, which may also trigger such events. Another difference is that huge subaerial proglacial and supraglacial lakes require uncommon situations – such as the blocking of a huge depression by the Laurentide Ice Sheet – and are consequently relatively rare phenomena. In contrast, an irregular bedrock topography – as present under the Antarctic ice sheet – favours the continuous presence of huge water reservoirs. These form potential sources of sudden giant meltwater outbursts that may result in megafloods that might carry such large ice masses to the ocean that Heinrich-like events (with the potential consequence of global cooling) could take place.

Discussion

The larger a subglacial sheet-like flood is, the larger the ice mass that can be transported 'on its back' to the ocean. No reliable and statistically significant data about the relationship between jökulhlaup frequency and jökulhlaup size are available. It is therefore impossible to estimate with any degree of certainty the frequency of megafloods that originate and develop underneath huge icecaps and that might transport such huge icebergs to the sea that a Heinrich-like event would result. Johnson & Lauritzen (1995) argue that many Heinrich events may be due to processes identical – or at least comparable – to those that induced the 116 ka cooling).

Considering the frequency of (mostly small to moderate) jökulhlaups in Iceland during the 19th and 20th century, and considering the fact that in nature the frequency of specific phenomena decreases with increasing size/ power, it must be considered very well possible that megafloods can occur underneath the land-ice masses of Antarctica every 10,000–100,000 years. Because the frequency of Heinrich events falls within this range, it would be scientifically challenging to evaluate the possibility that some phases of global cooling were – directly or indirectly – a result of surging that was triggered by extremely large subglacial floods. It may be true that 'real' Heinrich events are known only from the Atlantic (due to giant icebergs broken off the Laurentide ice sheet), but Heinrich-like events must also have occurred as a result of huge ice masses broken off the Antarctica ice sheet. This is indicated by significant layers of ice-rafted debris in the surrounding oceans (Hou et al., 1998) that coincide with low-temperature intervals on Earth, for instance 14.3–14.6 and 1.7–10.3 ka ago (Kanfoush et al., 2000). It should be kept in mind in this context that the existence of huge lakes on Antarctica, such as Lake Vostok, provides an ideal source for the water masses needed for such floods. Considering the occurrence of Heinrich events in the not so remote past, one could well imagine that the present-day conditions are still suitable for the occurrence of a new event: the ice or hardrock barrier damming off now the outlet of a sufficiently large subglacial lake may become overflown (or in the case of ice: undermined), triggering a giant subglacial outburst that could initiate a Heinrich event. The formation of a sufficiently thick lubricant layer with enough bearing capacity might have the same effect.

One might question why Heinrich events seem to have been restricted – or at least largely restricted – to the northern hemisphere (Scourse et al., 2000). This can be explained – if Heinrich events were triggered by catastrophic subglacial floods indeed – only by the fact that the conditions underneath the Laurentide Ice Sheet differed from those under the Antarctic ice cover. Analysis of such conditions (and their differences) is of great importance if the risk of megafloods under the Antarctic and the Greenland ice sheets is to be assessed. Relatively little is known about the Greenland conditions, as direct observations are impossible (Carter et al., 2009, call the transport of subglacial water "... an enigmatic and difficult to observe process"), and remote techniques (including geophysics) yield results that can, as a rule, be interpreted in various ways. One of the differences between Antarctica and Greenland is that the former is many times larger than the latter, whereas the ice-surface is more inclined in Greenland. In addition, it seems that the bedrock in the interior of Greenland does not have much relief. These two factors make the existence of numerous large subglacial lakes in Greenland unlikely; in fact no such lakes are known as yet from Greenland (M.J. Siegert, pers. comm., 2005). This is in strong contrast to the situation in Antarctica (Siegert et al., 2005) where subglacial lakes abound: apart from the 14,000 km^2 large Lake Vostok (Fig. 6), other subglacial lakes under Dome C amount to at least 15,000 km^2, and some additional 15,000 km^2 of subglacial lakes are known from under the remainder of the ice sheet. The total water volume underneath the ice is estimated to be 4,000–12,000 km^3, possibly some 7140 km^3 (Siegert, 2000), thus being much more than on Greenland. Moreover, the bedrock of Greenland has the shape of a bowl, which makes it much more likely that any hypothetical megaflood would be directed towards the centre than towards the margin of the icecap. It is interesting in this context that few lakes have thus far been interpreted underneath ancient icecaps; one example is subglacial Lake McGregor, supposedly present under the Laurentide ice sheet in south-central Alberta (Munro-Stasiuk, 2003).

Processes like the interplay between ice movement, water/ice interaction, and geothermal-heat transfer might play a part in the occurrence of giant water outbursts under the Antarctic ice sheet. Such outbursts may, however, be so far away from the ice front that – however large the outburst may originally be – the effects in the more marginal parts become small. The diminishing effect may be due to the distribution of the water over an ever increasing surface area, to re-freezing of the water, and/or to loss of current velocity due to friction. The result of the decrease of the flood's power with increasing distance from the place of origin may be that no huge ice masses may be triggered to move in the more marginal parts of the ice. In that case, even a giant water outburst in the central part of the ice sheet may remain unnoticed. Obviously, the fact that no such outbursts have ever been noticed along the margin of the Antarctic ice sheet might also be ascribed to their non-existence. It is, for instance, principally possible that, apart from the 68 lakes known to be present under the East Antarctic ice sheet (Vincent, 1999), there is insufficient air-filled space in the direct vicinity of lakes under the Antarctic ice sheet to allow these lakes to overflow into such spaces. Another aspect to be considered is the topography of the hard-rock substratum. One could imagine – but there are insufficient detailed data available as yet – that the topography under the Antarctic ice sheet is so irregular, for instance due to glacial erosion during periods with no or much smaller ice caps (cf. Engström et al., 2000), that lake levels cannot rise sufficiently to start overflow. It is also possible that the physical characteristics of the hard-rock barriers in Antarctica do not allow them to be eroded strongly enough to start catastrophic floods. More detailed seismic mapping might provide the necessary data, changing the above idea into a testable hypothesis (cf. Van Loon, 2004).

Final remarks

Little is known about the occurrence of meltwater outbursts in the more central parts of huge icecaps. It is not known, for instance, what precise processes might be involved. In addition, it is not understood why Heinrich events are known well only from the northern hemisphere, and only from the Laurentide ice sheet. It is not well understood either what is the reason behind the rough cyclicity of these events.

No attention has been paid thus far to a possible triggering of Heinrich events by the sudden, giant outbursts of subglacial lakes. Several characteristics of both subglacial megafloods and Heinrich events could, however, be explained well if such a relationship exists. Admittedly, several processes (such as acceleration of ice sheets by basal decoupling or enhanced bed deformation) have been proposed already, and the proposed processes seem feasible. This does not imply, however, that alternative explantions should not be considered (the number of possible causes of the mass extinction at the P/T boundary is ever growing!). It is therefore suggested here that the possibility of a possible relationship between subglacial megafloods and Heinrich-like events be further investigated, if only because of the probable consequences of future Heinrich-like events for the global climate. It should be noticed in this context that a subglacial volcano that was active only some 2000 years ago and that should therefore be considered as dormant rather than as extinct, has recently been discovered beneath the West-Antarctic ice sheet (Corr & Vaughn, 2008) and that its activity has already been related to increased flowage of Antarctic ice masses.

As it seems that meltwater discharges during deglaciation show a complex interrelationship with climate, landscape evolution and the mechanisms determining glacier movement, not only subglacial volcanism but also present-day global warming might favour the conditions under which the sudden release of giant masses of subglacial meltwater (cf. Carter et al., 2009) might trigger a Heinrich-like event, with global consequences for society. It is noteworthy to remark in this context that such an effect would induce a fall in temperature in large parts of the world, so that global warming might, in this respect, have a negative feedback.

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