



COLIN A. WHITEMAN

**COLD REGION
HAZARDS
and RISKS**

 WILEY-BLACKWELL

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Cold Region Hazards and Risks

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Dedication

To Mother and Father

Preface

Sometimes, in the Arctic, you just have to sit and wait. It is the nature of tundra travel that the weather plays a key role. If the fog is down the Cessna doesn't fly; but then there is time to sit and think, or catch up with reading, which is how I came to be in the library of the Aurora Research Centre, in Inuvik, NWT, Canada. A thick volume on Arctic contaminants (not actually included in this text) sparked a train of thought that led to cold hazards and risk, and the idea that this would make an attractive subject for undergraduate students. However, with the exception of avalanches, ice-related hazards very rarely feature in existing geohazards texts. There may be some geomorphological coverage of particular topics in specialist glacial and periglacial books but nothing that brings the full range of cryogenic hazards together within one cover. At the same time as this idea arose, climate change was receiving wide coverage in the media and the subject of environmental hazards was gaining popularity amongst students. Polar and alpine regions appeared to be most vulnerable to climatic warming and ice-related events were attracting more media coverage. Dramatic pictures of disintegrating Antarctic ice shelves were projected into our living rooms for the first time, an Alpine glacier received an insulating blanket to preserve it for skiing, and stirring tales of the 'Northwest Passage' were revived as Arctic sea ice retreated. With popular coverage of these issues growing, it seemed an appropriate moment to provide a broad physical and human geographical background to these and related cold region hazards.

This has not proved to be an easy task. At the same time as popular coverage was rising, scientists in all areas have been exceptionally busy seeking answers to these accelerating environmental changes in an effort to understand what is happening and provide some advice on

ways to reduce the potential impacts. Consequently the amount of literature on most topics is daunting. While adopting a global outlook in terms of the scope of examples, it has been necessary to be selective and apologies are due to those who feel that their work has been overlooked or inadequately handled. Nevertheless, I hope that there is sufficient scope and detail in each area to provide an understanding of the nature of the hazard, its potential impacts and the different approaches that have been taken to mitigate the hazard and limit risk.

For many reasons I must acknowledge a number of individuals and groups. Jim Rose is responsible for my interest in cold region geomorphology and geology. Julian Murton invited me to spend research time in the Arctic and, through our Inuvialuit assistants, Fred Wolki, Enoch Pokiak and Raymond Cockney, enabled me to gain a deeper understanding of Arctic life and environments. My colleagues in the Geography Division of the School of Environment and Technology at the University of Brighton kindly supported the cold region hazards module proposal, and some have even raised my awareness of human issues behind the physical environment. Their friendly rivalry provided a stimulating working environment under Roger Smith's able leadership. I have also received willing support from technical staff in the School and research assistant, Margaret Allen, has spent many hours in the search for appropriate material, as well as arranging two successful popular conferences related to polar environments which have raised the profile of cold environments within the School. At Wiley, I am grateful to Rachel Ballard for inviting me to submit the initial proposal and to unnamed colleagues who either reviewed the proposal or, subsequently, parts of the completed text, though I am responsible for any remaining errors. Also at Wiley, I am indebted to Izzy Canning, Chelsea Cheh, Aparajita

Srivastava and, especially, to my project editor, Fiona Woods, who has provided encouragement and the necessary drive to see this project to completion. Finally, I thank Jill for her patience and long-suffering support.

Colin A. Whiteman

1

Introduction

1.1 Concept and rationale

This book is about ice, and its associated hazards. Ice is implicated in the 1970 Huascarán disaster, which killed about 18 000 people in the Andes of Peru. In 1912 over 1500 people died when the *Titanic* struck an iceberg and sank during her maiden voyage across the Atlantic. Each year, about 150 people are killed by avalanches and in bad snow seasons, such as 1950–1951 in Europe, this number can nearly double. Occasionally, catastrophic avalanches, such as the one that struck Galtür, Austria, in 1999 killing 31 people (Keiler *et al.*, 2006), are widely reported, but most geohazard textbooks neglect geocryogenic hazards. Instead, attention is focused on tsunamis, earthquakes, volcanic eruptions, landslides and floods, hazards which, more frequently, cause larger numbers of fatalities.

A number of reasons can be suggested for this neglect of cold region hazards. One has already been mentioned: ice-related hazards, with the exception of some avalanches, are rarely dramatic. A second reason is that cold regions are inhospitable to many people and generally support only low densities of population. Consequently, large centres of dense population are rare, except in the European Alps, and few people are perceived to be at risk. Thirdly, the remoteness of many polar and alpine regions means that some hazards pass unrecorded or are at best underrecorded, until a more newsworthy event brings the hazard to a wider audience. For example, such an event

occurred in the Himalaya in 1985 when a glacial lake burst beyond its confining moraine and destroyed a small hydro-power plant that was about to be commissioned (Ives, 1986). In the context of this less-developed region, the ice avalanche that initiated this flood dealt a devastating blow to the aspirations of a financially poor community. On the other hand, this event was clearly instrumental in raising both national and international awareness of a Himalayan problem that has since received substantially more attention (see Chapter 6). Lack of awareness is a fourth reason geocryogenic hazards generally have such a low profile. Obviously there are exceptions, such as densely populated Switzerland which in many respects leads the world in its study of geocryogenic hazards (e.g. Haeberli *et al.*, 2009). Otherwise, even scientists (Solomon *et al.*, 2007) have been surprised at the rapid rate at which some geocryogenic systems are changing and becoming more hazardous. Until scientists realized what was happening, there was little chance that others – the media, the general public and politicians – would be aware of the increasing risks associated with geocryogenic hazards. If the number of fatalities is the only measure of hazard importance, then perhaps ice does not warrant any special attention. However, in the present context of rapid climate change, ice-related hazards assume a much greater significance. In this text a broader, longer-term approach to hazard and risk will be taken, involving the social, cultural and economic well-being of human societies, and the biodiversity of natural ecosystems.

1.2 Scope and classification of the hazards

Most people are familiar with *snow* avalanches (Chapter 8), even though they may never have seen one, or even

travelled through alpine terrain where these phenomena are common, but how many people have heard of *ice* avalanches (Chapter 5)? Likewise, many individuals will know of icebergs (Chapter 4), if only through the medium of film – blockbusters such as *Titanic* have seen to that – but how many people are familiar with other types of floating ice such as sea ice (Chapter 2) and ice shelves (Chapter 3)? Some ice-related hazards are unobtrusive because the ice is mostly out of sight below the ground surface. Permafrost (Chapter 7) falls into this category. Those of you reading this in a temperate maritime environment, or in the tropics or subtropics, may not even have heard of river ice jams (Chapter 9) and ice storms (Chapter 10). However, these hazards are familiar to the inhabitants of continental interiors (the northern states of the USA and the southern provinces of Canada, for example) and more northern latitudes, where subzero winter temperatures are normal. The television programme, *Ice Road Truckers*, has brought another hazard of polar and northern regions, ice roads (Chapter 9), to the attention of a wider audience. Two other hazards will be considered. One is the ice sheets (Chapter 3) which have the potential between them to raise sea levels by a massive 70m, though hopefully not all at once! The other is the blizzard (Chapter 10) which may constitute the most widespread of cold region hazards as it depends on the global atmosphere.

At this stage, it is worth attempting some degree of hazard classification ([Table 1.1](#) and [Figure 1.1](#)), in order to make sense of their different characteristics and to clarify their interrelationships with each other and with the human context. Any system of classification is likely to be a simplification of reality: some hazards are extremely complex. For example, the large terrestrial ice sheets have fast-moving components (ice streams) as well as what might be described as normal, slow-moving areas.

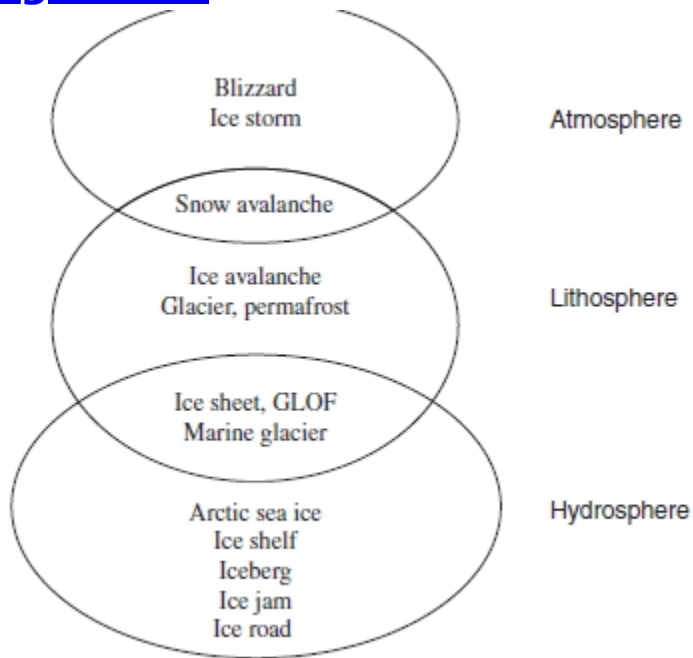
Additionally, it is now apparent that the behaviour of these ice sheets cannot be adequately modelled without also considering adjacent ice shelves and the surrounding, seasonal sea ice. Nevertheless, for the purposes of this exercise, ice sheets and glaciers will be considered generally as large, slow-moving, often land-based (terrestrial) masses of solid ice, possibly 3-4 km in thickness in the case of ice sheets, and with the potential to alter the global distribution of land and sea significantly. They can be contrasted with floating ice, such as sea ice and river ice which may average only 3-4 m in thickness and be seasonally very variable in extent. However, while the hazards of river ice are very localized and seasonal, the potential effects of sea-ice hazards may be felt much more extensively in both space and time. Ice shelves and icebergs are other forms of floating ice but in both cases these have a link to land-based ice. Ice shelves are largely an extension of land-based ice sheets, while icebergs are free floating, mobile ice bodies that have calved from land-based ice or ice shelves, and are potentially more difficult to deal with. In contrast to the hazards mentioned so far, which are terrestrial or water-based, ice storms and blizzards are essentially atmospheric in context and closely controlled by weather systems. Consequently, their impacts can be sudden and the distribution of their impacts in both space and time difficult to predict. Another sudden and often unpredictable hazard is the snow avalanche. Although it occurs on land, atmospheric conditions are the essential prerequisites of this hazard. Weather systems deliver the snow and may then metamorphose it into a susceptible snowpack. Two glacier-related hazards not mentioned specifically so far are ice avalanches and glacier lake outburst floods (GLOFs). Unlike snow avalanches, ice avalanches depend on the structure and position of the glacier from which they originate, although their impacts can achieve the same ends as snow avalanches -

instantaneous death and destruction of property. GLOFs are not geocryogenic per se but they derive from glacial contexts and are often very difficult to predict. Their impacts are confined to glacial valleys but may be very variable in extent. The final hazard to be mentioned is permafrost, a unique hazard in the sense that it occurs *beneath* the surface, usually on land but also under some coastal seas. Depending on the content of ice in the permafrost, this hazard could directly impact up to 25% of the Earth's surface, perhaps more than any other cold region hazard, if the impacts of other hazards on the global atmosphere are discounted.

Table 1.1 Hazard characteristics

Hazard type	Hazard process	Impact			Timing			Term			Global context	Latitudinal context
		Direct	Indirect	Sudden	Gradual	Short	Medium	Long				
Arctic sea ice	Impact, crushing, erosion, surface failure, albedo change	x	x	x	x	x	x	x	Hydrosphere	Polar		
Ice sheets	Sea level rise, albedo change, climate change		x		x		x		Lithosphere, hydrosphere	Polar, sub-polar		
Ice shelves	Iceberg impact, glacier acceleration	x	x	x	x	x	x	x	Hydrosphere	Polar, sub-polar		
Icebergs	Impact	x		x		x			Hydrosphere	Polar, sub-polar		
Glaciers	Impact (seracs), land burial, slope instability	x	x	x	x	x	x	x	Lithosphere, hydrosphere	Polar to tropical Alpine		
GLOFs	Flood		x			x			Lithosphere, hydrosphere	Polar to tropical Alpine		
Permafrost	Ground instability	x		x		x			Lithosphere	Polar, Alpine		
Snow avalanches	Impact and burial	x		x		x			Lithosphere, (atmosphere)	Polar to tropical Alpine		
Ice avalanches	Impact and burial	x		x		x			Lithosphere	Polar to tropical Alpine		
Ice jams	Impact and flood	x	x	x		x			Hydrosphere	Polar to temperate		
Ice roads	Surface failure	x		x		x			Hydrosphere	Polar to temperate		
Blizzards	Excessive snow deposits, gale force winds	x		x		x			Atmosphere	Polar to tropical Alpine		
Ice storms	Excessive ice deposits, structural collapse	x		x		x			Atmosphere	Polar to temperate		

Figure 1.1 Global context of cold region hazards



1.3 Hazard awareness

Probably nothing has done more to enhance our awareness of the hazards of cold regions than climate change, because by definition cold region hazards are climate and weather dependent, and ice depends on temperature for its behaviour and, indeed, for its very existence. The Earth's environment has always been in a state of flux, ever since it was a cloud of dust and gas 4.6 billion years ago. Some periods during this time have been relatively stable; others have experienced rapid change on a massive scale. The Earth system is often subdivided into the lithosphere (rock), hydrosphere (water), atmosphere (air), biosphere (fauna and flora) and *cryosphere*, the latter composed of ice, and the component least familiar to the majority of people. However, the cryosphere is arguably the single component of the global environment that has changed most noticeably. During the last few million years the Earth has fluctuated between glacial periods, when ice sheets and

glaciers advanced across the globe, and interglacial periods, when ice has been forced to retreat. The last major ice retreat phase began about 15 000 years ago and for the last 11 500 years the Earth has experienced an interglacial phase. There have been minor fluctuations during this interglacial period, such as the Little Ice Age, when alpine glaciers presented a new hazard as they advanced down their valleys, but for over a century that trend has been reversed. The last 30 to 40 years have seen a period of rapidly rising temperature, especially in the Arctic, but also in alpine regions. Most glaciers are in retreat mode, sea ice on the Arctic Ocean has thinned and its area decreased, and permafrost has warmed. Even the great Greenland Ice Sheet has shown signs of increased melting.

Although climate change waxes and wanes as an issue in the media, it is now difficult to avoid, in one context or another. High profile reports of the Intergovernmental Panel on Climate Change (IPCC), the latest in 2007, and the Arctic Council's Arctic Climate Impact Assessment (ACIA, 2004) have achieved wide publicity. Consequently, the narrow, traditional view of geo-hazards, largely excluding the cryosphere, is slowly beginning to change. Television and newspaper correspondents are increasingly filing their reports from the decks of polar ice-breakers or the holds of helicopters as they seek to explain the decay of Arctic sea ice, or the disintegration of yet another Antarctic Peninsula ice shelf. Today, 8 April 2010, before I sat down to write this, BBC TV Breakfast News (BBC NEWS, 2010b) informed viewers that the replacement satellite (Cryosat-2) for the one that blew up during take-off in 2005, had been launched. The BBC statement was accompanied by a simple animated diagram illustrating how the satellite would record Arctic sea ice thickness, a crucial function in tracking changes to this important component of the cryosphere. If Arctic sea ice completely disappears, it must have an

impact on climate because its current function as a reflector of solar radiation would be lost. Of more immediate concern is the effect it would have on Arctic inhabitants, especially the indigenous populations. Until recently Inuit traditional knowledge served a vital purpose in keeping hunters safe on the sea ice. Now, it is not uncommon to hear complaints that traditional knowledge is no longer 'fit for purpose' in some areas of Arctic sea ice (Ford, Smit and Wandel, 2006). Rapidly thinning and retreating ice is forcing a rethink, and the Inuit are facing steep 'learning curves' to keep up with changes in their once familiar territory. Winter hunting seasons are becoming shorter as access to the sea ice becomes less easy and more dangerous.

In August 2003, during the European Permafrost Conference in Zurich, the convener of the meeting, Professor Wilfried Haeberli, was called to the television studios to explain possible reasons for a massive rockfall from the slopes of the famous Matterhorn mountain in Switzerland (ETH Life, 2008), where several climbers were trapped until they could be airlifted to safety. About the same time, climbers following a route to Mont Blanc, in France, were less fortunate when they were hit and killed by another rockfall (Summitpost, 2003). It is likely that these headline-catching events were induced by the melting of mountain permafrost. An increasing number of landslides and rockfalls in the European Alps are close to the lower margin of mountain permafrost where the decay of this hazard is concentrated as the global temperature rises (ETH Life, 2008). For economic reasons, glaciers have been covered with insulating membranes to reduce summer melting and help preserve the valuable winter skiing industry (BBC NEWS, 2005).

Some ice-related hazards provide the media with spectacular footage for their prime-time news broadcasts, so we are now able to see massive tabular icebergs drifting

away from their parent ice shelf in Antarctica (BBC NEWS, 2002). It is extremely unlikely that anyone will die as a *direct* consequence of the disintegration and melting of an ice shelf, but it has been shown that land-based ice streams within the West Antarctic ice sheet (WAIS) have accelerated and calved into the ocean once the protective ice shelves have gone. As these ice streams are land-based, their melting causes global sea level to rise. Although this sea-level rise will almost certainly be too slow to be directly life-threatening, it nevertheless has the potential to achieve this result *indirectly* through its impact on vulnerable economies such as Bangladesh.

These news stories, from which the general public derive so much of their information about scientific issues (Allan, 2002), are themselves derived largely from the press releases of research organizations, from individual scientists, or from scientific journals and other publications. In recent years a great deal of this new information on cryospheric subjects has come from the rapidly advancing, remote sensing capabilities of satellites, such as Landsat 1-5, ERS 1-2, RADARSAT 1-2, ICESat and the recently-launched Cryosat-2 (*The Satellite Encyclopaedia*, 2010). Regular monitoring of the cryospheric system, since the emergence of scientific satellites in the 1970s, has greatly facilitated the research effort, especially in remote and difficult terrain. However, this constant monitoring generates unprecedented quantities of data and this is increasingly being organized into accessible databases on a wide range of subjects such as glaciers, permafrost, ice jams, icebergs and GLOFs (glacial lake outburst floods). One important outcome of this constant effort is a new awareness of, and deep concern about, the *rapid* rates of change of some geocryogenic systems such as ice sheets, glaciers and Arctic sea ice. This has enabled the IPCC (Solomon *et al.*, 2007) to raise the probability of some of its

predictions about the cryosphere from 'likely' to 'very likely' and has undoubtedly stimulated the interest of governments and grant-awarding bodies in new cryospheric research. In turn, this should enhance understanding of cold region hazards and the dangers associated with ice.

1.4 Physical properties of ice

Ice is a complex material. Under certain conditions it is a relatively hard, strong solid, capable of smashing buildings and sinking ships. However, under stress it can exhibit elastic, ductile and brittle behaviour (Knight, 1999). This means that glacier and sea ice can deform or crack under different conditions. Tensional stress, as glaciers accelerate on steep slopes, causes cracking and the formation of crevasses. These are a hazard for unwary mountaineers and may cause masses of ice to avalanche from the end of a glacier, or marine glaciers to calve an iceberg. In other circumstances, cold ice can form strong bonds with rock and maintain the stability of rock faces. If, however, the temperature rises *above* 0 °C, ice melts and takes on the properties of water, a relatively weak, mobile fluid. Melting ice-rich permafrost can cause slope instability resulting in rockfalls, landslides or debris flows. In the right circumstances, snow, composed of ice crystals, may be stable on a slope but if the conditions change the snowpack can become unstable and detach from the slope as an avalanche.

In addition to these changes in material strength, there is also a significant volume change across the 0 °C temperature threshold: ice occupies approximately 9% more space than the equivalent amount of water. Consequently ground can heave as its temperature falls past zero degrees and moisture freezes, and can subside as the temperature rises past the same threshold and ground-ice melts. This

volumetric change is a major hazard of permafrost regions. Given that the *average* temperature of the Earth is around 13 °C, often only a small fluctuation in actual temperature is required to bring about some quite dramatic changes in the environment.

Under cold polar conditions the whole of the sea surface can freeze to form a layer of ice a few metres thick. This happens over most of the Arctic Ocean and around the continent of Antarctica. As will become clear in the following chapter, stable sea ice can be an asset to humanity, but as it moves under the influence of winds and sea currents, and as its extent increases and decreases seasonally, it can create hazardous conditions. Ice also forms on rivers where it can again be hazardous, especially if it breaks up and forms jams of ice blocks, or if it is too thin to support the movement of vehicles and people.

On land, similar cold conditions in both high-latitude and high-altitude regions can cause snow to accumulate which gradually transforms into glacier ice. Under the influence of gravity ice moves, either slowly by the deformation of individual crystals (creep), or more rapidly by basal shearing, basal sliding or with the aid of deforming subglacial sediments (Knight, 1999). The usual rate of flow of glaciers and ice sheets (exceptionally ~19 m per day (e.g. Jakobshavn Isbrae, Greenland) but generally much less) is not normally hazardous. When the input (snow accumulation) and output (ice ablation or melting) of a glacier are in balance the main dangers to be aware of are crevasses and falling seracs on the glacier surface. The bigger problems arise, either directly or indirectly, when glacier margins advance or retreat as mass balance increases or decreases. Providing glacier ice remains in an impermeable state with limited crevassing it is capable of damming the flow of water derived either from the melting of the glacier itself or from normal surface run-off. Lakes on

and around glacier margins can lead to disastrous floods unless their behaviour is seasonally predictable. In coastal areas ice can be transferred from the land onto the sea, as either floating ice shelves or ice bergs. Under normal conditions ice shelves remain attached to the land ice and present relatively little danger. They create problems when they disintegrate by forming massive tabular icebergs and by allowing the terrestrial ice to accelerate. Icebergs, on the other hand, float free and are a constant direct hazard to both shipping and fixed installations until they melt.

1.5 Hazard and risk

Without doubt ice in its various environmental manifestations can be a dangerous material and give rise to disastrous events. When these ice-related features have the potential to impact negatively on humans, their possessions and their general environment, they become *hazards*. Potential hazards are always present in the landscape but not necessarily a constant threat. The more that is known about how hazards function, the easier it is to predict hazardous events. As will become clear when considering individual hazards, monitoring, mapping and interpretation are key requirements for assessing the level of *risk* attached to a particular hazard. Monitoring may vary from the daily, practical measurement of snowpack on a hillside to remote sensing by satellite. Remote sensing, in particular, has enabled significant progress to be made in the fields of mapping and monitoring, and the results of this work suggest that the risk of some of the hazards considered here is increasing significantly.

Risk is a combination of the probability that an event will occur, and the likely cost of the event. Essentially, risk is the product of frequency and magnitude. It can be defined by a simple equation:

$$\text{Risk} = \frac{\text{Hazard probability} \times \text{Expected loss.}}{\text{Loss mitigation}}$$

The probability of a hazardous event is usually determined from historical data. Longer time series enable more accurate predictions to be made. Risk managers often refer to a design event; that is an event of a particular magnitude and frequency around which they design their mitigation response. Normally, larger events recur less frequently than small events. Recurrence interval, probability and annual frequency of an event can be calculated as follows:

$$\text{Recurrence interval, } T_r (\text{years}) = (n + 1)/m$$

where m = event ranking (largest to smallest) and n = number of events in the time period.

$$\text{Probability of event, } P (\%) = 100/T_r.$$

$$\text{Annual frequency, } AF = 1/T_r (\text{years}).$$

For example, in a list of 50 (n) events the largest event ($m = 1$) will have a recurrence interval of 51/1 which is 51 years. The smallest (50th) event will have a recurrence interval of 51/50 which is 1.02 years, that is it occurs almost annually. The same largest and smallest events would have a probability of 1.96% and 98% and an annual frequency of 0.02 and 0.98 years respectively.

Expected losses from a hazardous event can be calculated from a knowledge of the number of people living within the expected range of the event and the value of their property. One factor that is contributing to risk in many areas is increasing population density coupled with the migration of residents and tourists into more remote and hazardous areas. Natural environmental costs may also be taken into account. The total value of loss can be reduced providing appropriate *mitigation* measures are put in place to reduce impact. Effective mitigation relies on a sound knowledge of hazard mechanisms. For example, in avalanche-prone areas,

structures can be modified and buildings restricted by a system of land-use planning or zoning. The avalanche events themselves can sometimes be modified by inducing the avalanche before the snowpack becomes excessively deep and the potential volume of snow dangerously large. Mitigation of a hazard can also be achieved by forecasting, based on historical records, and effective warning procedures. Sometimes evacuation may be necessary. Mitigation can also be achieved through the education of both the community involved and responsible authorities at both national and international levels. Communities where mitigation is poorly developed, for reasons of inadequate wealth or ignorance, will obviously be more vulnerable to the impacts of hazards than those living in more favourable circumstances. Wealth and knowledge will also influence the adaptive capacity of communities, as will their resilience. At present, some of the hazards, such as ice-sheet melting, appear to be changing slowly relative to the capacity of communities and individuals to adapt. However, whether the long-term consequence of this impact – a rise in sea level – will always be equally manageable, remains to be seen. Arctic coastal communities, as noted earlier, are already being forced to respond to another massive hazard, the decline in the extent and thickness of sea ice. Many countries with cold regions are reviewing the level of risk presented by their geocryogenic hazards, redesigning their building and land-use regulations or making plans to resettle vulnerable communities.

1.6 Summary

Although technical specialists may have been aware of the hazards of particular cold environments, for a number of reasons details have rarely been included in geohazards texts, although may be this is about to change. While the

direct effects of avalanches and icebergs may be familiar, the impacts of many other hazards of cold regions are less direct and less well known. However, with the well-publicized possibility that global temperature could rise by as much as 3 °C within the next few decades (Solomon *et al.*, 2007), more people are becoming aware of potential hazards, especially those associated with melting ice. As ice changes into water, the volume of material decreases, ground subsides, slope stability declines and lake levels rise (or lakes disappear altogether if the base of permafrost is penetrated). Also, coasts become increasingly exposed to storms as sea ice retreats, shrinking glaciers and rising snow lines reduce potential stores of water for irrigation and hydroelectric power, and the scope of traditional alpine tourism decreases. Many people, far beyond the limits of conventional polar and alpine 'cold regions', will feel the effects of these changes in the cryosphere as global sea levels rise. Given this rapidly changing global context it seems appropriate to bring geocryogenic hazards to a wider audience. With this in mind, each of the following chapters addresses the scientific background of a different set of geocryogenic hazards, assesses the risks faced by both humanity and natural ecosystems and considers appropriate methods for mitigating the impacts of each hazard.

2

Arctic Sea Ice

2.1 Introduction

Under long-term, north-polar-average conditions, Arctic Ocean water is cold enough to freeze. In winter the ocean is largely covered by at least 2-4 m of ice ([Figure 2.1](#)), except for the region north of Scandinavia which is warmed by the Gulf Stream (North Atlantic Drift) ([Figure 2.2](#)). The area covered by sea ice contracts during the summer to a minimum around mid-September, as the Arctic warms, and then expands again during the winter to a maximum in March. In the past, and still today, Arctic sea ice presents a hazard to shipping and other off-shore activities as its mass and movement is capable of crushing vessels. However, in 2007 Arctic sea ice made headlines in newspapers around the world for a different reason (BBC NEWS, 2007). A dramatic reduction in the area of ice on the Arctic Ocean, at its annual September minimum, produced speculation by Wieslaw Maslowski that an ice-less Arctic Ocean would occur as early as the summer of 2013. More realistic estimates by Peter Wadham (“earlier than 2040”) and Mark Serreze (“2030”) are not unreasonable following three more years when the summer ice minimum has failed to reach the 1979-2000 average ([Figure 2.3](#)). As will become clear, sea ice can be a hazard when it is present, and also when it is not present.

Many expeditions, some searching for the elusive ‘Northwest Passage’ as a short cut between Europe or north eastern North America and Asia, have become trapped and