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THE CRYOSPHERE AND GLOBAL ENVIRONMENTAL CHANGE

by

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PREFACE

This book attempts to deal integratively with all elements of the cryosphere in the context of a changing global environment. Not only is that global environment changing with respect to climate, but the accelerating pressures on the environment from anthropogenic activity are complicating our understanding of cryospheric change. The cryosphere is an essential member of the globe's environmental systems. Relatively few recognize the sheer extent of snow, ice, and permafrost environments, much less the critical regulatory function of the cryosphere subsystem within the global environmental system. We therefore offer this book as a contribution to the Environmental Systems and Global Change Series and aim at meeting the objectives that are common to that series, as follows:

1 to create an awareness and understanding of the way in which the cryosphere is responding, has responded, and continues to interact with the changing global environment;

2 to explore the pace and extent of global environmental change and to show how the cryosphere responds to change over a variety of scales of time and space;

3 to attract upper level undergraduate students from a range of disciplines and to encourage them to think in new ways that transcend traditional disciplinary boundaries;

4 to underline the relevance of these changes to social and environmental problems and to encourage students to bring a scientific approach to solving such problems.

The topic of snow, ice, and permafrost response to global environmental change and the implications for landscapes and human livelihoods has become a central concern over the past decade. Both within the deliberations of the Intergovernmental Panel on Climate Change (IPCC) and as the primary focus of reports such as the Arctic Climate Impact Assessment (ACIA 2004), the accelerating rate of change of the cryosphere has been emphasized. There are many specialized treatises dealing with individual components of the cryosphere, such as Siegert (2001) on ice sheets or even two of the components, such as Bamber and Payne (2004) on ice sheets and sea ice. None, as far as we are aware, deal with all six components of ice sheets, sea ice, snow, river and lake ice, glaciers, and permafrost. The reason has become evident in the course of preparation of this book. There has had to be sacrifice of considerable depth of discussion of each component. However, we are convinced that the task of synthesis, the comprehensive completion of which still lies ahead, is just as urgently needed as the in-depth analysis of each component of the cryosphere.

In order to avoid repetition within the text, we have decided to list the major findings of the IPCC and the ACIA, which are specifically relevant to our theme. Changes identified by the IPCC with intermediate to high confidence levels and which specifically affect or are affected by the cryosphere (McCarthy et al. 2001) are the following:

A Changes documented from available data:
  a. In the Arctic, increase in air temperature over land of as much as 5°C has occurred during the 20th century but only a slight warming over sea ice between 1961 and 1990 has been documented.
  b. Arctic sea ice extent has decreased by 2.9% per decade over the 1978–96 period.
  c. Regions underlain by permafrost have been reduced in area and a general warming of ground temperatures has occurred.
  d. A decrease in spring snow extent over Eurasia has occurred since 1915.
  e. A warming trend in the Antarctic Peninsula is evident.
  f. Between the mid-1950s and the early 1970s, Antarctic sea ice retreated south by 2.8° of latitude, but no significant change occurred between 1973 and 1996.
  g. Surface waters of the Southern Ocean have warmed and become less saline.

B Major changes predicted by climate models under a doubling of CO_2 scenario:
  a. Increased melting of arctic glaciers and the Greenland Ice Sheet will occur. Most of the Antarctic Ice Sheet is likely to thicken as a result of increased precipitation.
  b. Warmer water in the Southern Ocean will intensify biological activity and growth rates of fish.
  c. Summer ice in the Arctic Ocean could shrink by 60% and Antarctic sea ice volume could decrease by 25%.
  d. Thickening of the active layer will lead to widespread thermokarst and damage to infrastructure.
  e. There will be a weakening of the global thermohaline circulation as a result of increased flux of freshwater from the Arctic Ocean and consequent risk of rapid climate change, especially in Europe and the North Atlantic region.
  f. Changes in sea ice will alter the seasonal distribution, geographic ranges, patterns of migration, nutritional status, reproductive success, and abundance and balance of species.
  g. Polar regions are major sources and sinks for carbon dioxide and methane; projected climate change will increase contributions to greenhouse gases (GHGs).
  h. The Arctic is extremely vulnerable and major ecological, sociological, and economic impacts are predicted.
  i. Habitat loss for certain species of seal, walrus, and polar bear is anticipated.
  j. Loss of sea ice in the Arctic will provide increased opportunities for new sea routes, fishing and new settlements but also for wider dispersal of pollutants.
  k. Traditional life styles will be seriously affected. Maintenance of self-esteem, social cohesion, and cultural identity of communities will be the greatest threat.

Major recommendations of the Arctic Climate Impact Assessment Report (2004; ACIA), whose findings are generally consistent with those of the IPCC above, include ways of improving future assessments:

A improvement of subregional scale impacts, perhaps at the local level, where an assessment of impacts has the greatest relevance for residents;

B socioeconomic impacts in oil and gas production, mining, transportation, fisheries, forestry, and tourism need to be quantitatively determined;

C vulnerability or the degree to which a system is susceptible to adverse effects of multiple interacting stresses requires better understanding of the capacity of the system to adapt. In ecological context, vulnerability is commonly expressed as a function of sensitivity (response time following disturbance) and resilience (ability to absorb the effects of a disturbance).

But in order to achieve priorities A, B, and C, improvements in long-term monitoring, process studies, modeling, and analyses of impacts on society will be needed.

Much of this book is concerned with the identification of the state of our understanding of past and present interactions of cryosphere and changing environments. We have deliberately downplayed the prediction of future changes on the pragmatic and philosophical grounds that the future is, in principle, unknowable. But we do consider the very real probability of future collapse of both cryosphere and related socioeconomic systems.

In Chapter 1, we identify some of the most important systemic and cumulative changes in snow, ice, and permafrost that are likely to occur at global and circumpolar scales under the influence of climate and humankind. In Chapter 2, we address the measurement and monitoring problem; paying particular attention to ways of integrating observations over larger areas. In Chapter 3, we enquire into the role of the cryosphere as energy regulator and water store at local and micro-scales and examine the spatial variability of the cryosphere at global and circumpolar scales. In Chapter 4, we illustrate the dramatic ways in which remote sensing and satellite imagery have revealed spatial patterns of the cryosphere. In Chapter 5, we review our understanding of temporal variability of the cryosphere, with particular emphasis on the critical transition from glacial to postglacial conditions. In Chapter 6, we show the spatially variable imprint of the cryosphere on landscape. We view the landscape as a palimpsest, made up of successive layers of erosional and depositional evidence. In the final chapter, we discuss possible future transitions of the society–environment relation, the sustainability of the cryosphere, and the potential for cryospheric and societal collapse. The key themes that unify the book are:

A the unique sensitivity of the cryosphere as an indicator of change at all spatial and temporal scales;
B the transient nature of environmental responses of the cryosphere to disturbance by climate and/or human activities;
C transient facies, landform, and landscape responses to changing cryospheric conditions and the nature of the resistances to change, whether inherent to the cryosphere or ecologically, socioeconomically, politically, or culturally induced.

The senior author spent the early part of his career investigating snow quantity and quality variations in relation to runoff and sediment sources in the Coast Mountains of British Columbia. More recently, he has become impressed with the importance of the meta-problem of global environmental change in both its natural science and social science formulations. It therefore seemed appropriate to connect these two sets of interests at widely differing spatial scales. It became apparent that the area of remote sensing and geomatics would be essential and it was most fortunate that the junior author was willing to lend his expertise to this project. Without his coauthorship, this book would have been less scientifically credible.

Acknowledgments

The senior author acknowledges the beneficial influence of a year as Distinguished Scholar in Residence at the Peter Wall Institute for Advanced Studies during calendar year 2005. The inspiration provided by the 2005 cohort of distinguished scholars

(Drs. Dom Lopes, Ken Carty and Lawrence Ward), by the Peter Wall Distinguished Professor, Dr. Brett Finlay, and by the Director of the Institute, Dr. Dianne Newell, is deeply appreciated.

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The coauthors acknowledge their special indebtedness to Eric Leinberger and Dr Dori Kovanen. Eric is a superb cartographer who has redrawn and improved each of the maps and line drawings; Dori understands the science and has corrected many points of detail. Without Eric and Dori, this book would not have been so attractively illustrated and accessible.

We also offer our appreciation to the staff at Blackwell Publishing: Ian Francis, Delia Sandford, and Rosie Hayden. Their collective confidence in the original project proposal has been sustained even as their patience has been strained.

Finally, to two anonymous reviewers we are deeply grateful. One North American and one European expert took the time to save us the embarrassment of omitting some critical references and one or two errors of judgment. Nevertheless, remaining errors are the sole responsibility of the authors.

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1

THE EVIDENCE FOR CRYOSPHERIC CHANGE

1.1 Introduction

The cryosphere (the subsystem of the Earth characterized by the presence of snow, ice, and permafrost) plays a vital and central role in changes occurring in the Earth's environment. Several General Circulation Models have predicted that global warming will be first obvious and most extreme in polar regions. This is because snow cover, glaciers, and sea ice will all tend to diminish, and this will produce further warming because of the decrease in albedo associated with the greater extent and duration of dark surfaces (i.e. the Earth's surface absorbs more solar radiation). At the same time, the thawing of permafrost will release methane and greenhouse gases (GHGs) which will further warm the globe.

These feedback effects are fundamentally caused by some unique properties of water at the surface of the Earth that make it particularly susceptible to change. It is particularly important to the dynamics and energetics of the Earth's system that all three phases of water (solid, liquid, and vapor) coexist over the range of the Earth's temperatures and pressures. The sensitivity of water to the normal range of the Earth's temperature and pressure conditions is such that change of phase from liquid water to solid ice and vice versa occurs frequently. On no other planet within the solar system is this the case (Fig. 1.1). This particular change of phase leads to a dramatic change in surface cover characteristics which can be observed, measured, and sensed remotely. Further, this change of phase introduces a different set of energy and mass exchanges at the surface that may in turn produce a positive feedback that reinforces environmental changes induced by the phase change (see Chapter 3).

However, a single focus on climate is likely to be counterproductive in the interpretation of environmental change (Slaymaker 2000, 2001; Dowlatabadi 2002). Land use change is the other major driver of global environmental change

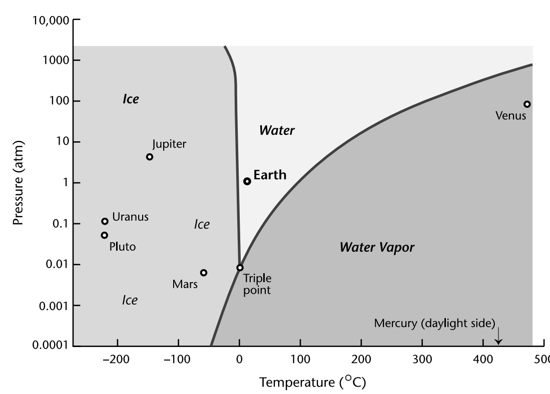

Fig. 1.1 Planetary positions on the phase diagram of water (from National Academy of Sciences 1991).

(Adger & Brown 1994). Such human activity also leads to dramatic changes in surface cover characteristics, thereby causing new energy and mass balances leading to land degradation. In fact, any surface cover change, whether natural or anthropogenic, causes changes in energy and mass balance that can have dramatic effects on the landscape. In permafrost environments, such effects are magnified throughout the active layer, which is that depth of soil, etc. which overlies the permafrost and melts on an annual basis. Road and runway construction on massive ice-rich permafrost leads to warming, land subsidence, and destruction of the transport corridor.

The impacts of changes are more difficult to understand and predict when several processes of change happen simultaneously. They are still more challenging when the systems are near a threshold (Slaymaker 1990). In this sense, we need to consider the fact that different populations of physical systems, ecosystems, and human systems are at varying distances from thresholds. The most vulnerable subpopulations in polar regions, whether permafrost, plants, penguins, polar bears, or people, are teetering on the edge of viability. Within the cryosphere, the critical threshold is the freezing point of water; in the ecosystem and human system, the presence or absence of snow and ice may be only one of several thresholds that needs to be considered.

We normally think of the following compartments of the cryosphere: seasonal snow, mountain glaciers and ice caps, ice sheets and ice shelves, permafrost, seasonal frozen ground, river and lake ice, and sea ice. Seasonal frozen ground has the largest area of any component of the cryosphere: at its maximum in the northern hemisphere winter it covers over 5.2 (10^7) km^2 (or about 50% of the northern hemisphere land mass; National Snow and Ice Data Centre (NSIDC) new data set; Zhang et al. 2005); ice sheets contain the largest proportion of the volume of the cryosphere at about 3.3 (10^7) km^3 (Fig. 1.2). These areal and volumetric data are important, but because of our interest in changes, it is the sensitivity of the various compartments to environmental change that is most important (Table 1.1). From this perspective, snow, lake and river ice, sea ice, ice caps and glaciers, seasonal frozen ground, and permafrost are more important than the 98.5% of the ice that is stored in the polar ice sheets and ice shelves. Snow is sensitive to individual weather events as well as seasonal fluctuations and climatic trends over decades and longer; river, lake, and sea ice are sensitive to seasonal fluctuations and longer trends; permafrost and glaciers are sensitive to decadal and longer climatic trends; and ice sheets are sensitive to millennial and geological timescale events. The precise sensitivities are not known in general and the question of threshold exceedances is a lively research topic.

Global environmental change is defined as environmental change that consists of two components, namely systemic and cumulative change (Turner et al. 1990). Systemic change refers to global scale, physically interconnected phenomena whereas cumulative change refers to unconnected local to intermediate scale actions which have a significant net effect on the global system. The coupled ocean–atmosphere system is an example of the former; land cover and land use changes produce cumulative change. Systemic changes are conceptually and intuitively obvious, but difficult to measure. Cumulative change is relatively easy to measure at a specific site or within a region, but the global impacts are often not simply additive. Feedback effects, both positive and negative, and variations in the levels of threshold exceedance complicate the calculation.

Our interest then goes beyond the topic of climate change but is more circumscribed

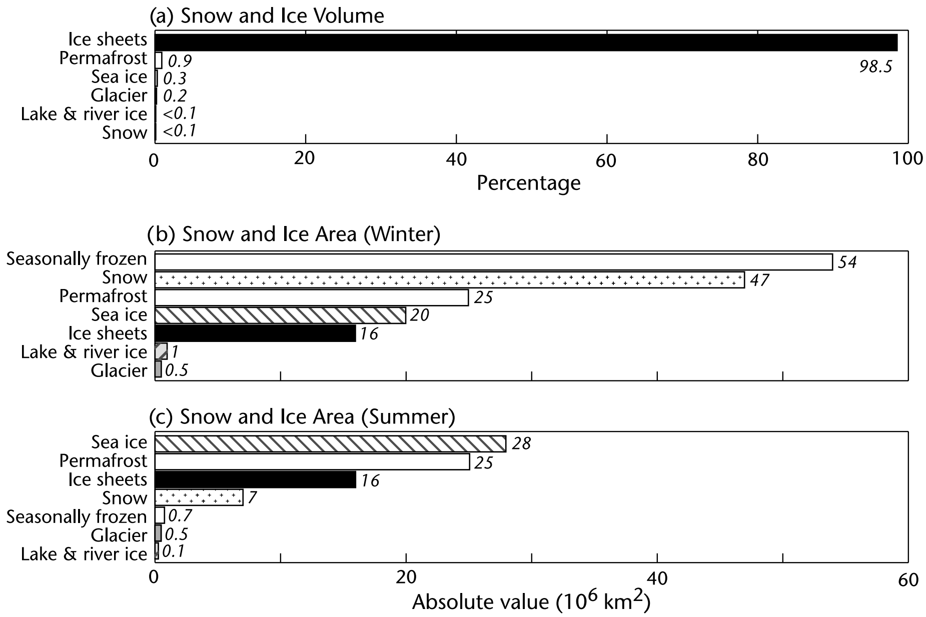

FIG. 1.2 Components of the cryosphere expressed as (a) percentage of total and (b) and (c) absolute values (Fitzharris 1996).

than the generic term "global change." The study of global change includes the full range of globalization processes, economic, social, cultural, and political, whereas global environmental change includes only the biogeochemical processes and the extent to which they are being modified by human activity (Slaymaker & Spencer 1998).

TABLE 1.1 Sensitivities of cryosphere compartments (after McGuffie & Henderson-Sellers 1997).

I Component	Response time
Sea ice	Days to centuries
Snow and surface ice	Hours
Lakes and rivers	Days
Soil and vegetation	Days to centuries
Glaciers	Decades to centuries
Ice sheets	Millennia
Mantle's isostatic response	Millennia

Global environmental change then, for the purpose of this book, occupies an intermediate slot between the almost limitless topic of global change and the more narrowly constrained field of global climate change.

There are several reasons for a new emphasis on global environmental change and these reasons emerged during the last four decades of the 20th century. In the 1970s, we first saw the Earth from space. We perceived an island Earth surrounded by the atmosphere and oceans and an Earth overwhelmingly dominated by water (the Blue Planet). This awareness forced an adjustment of our scientific scale of enquiry from site, plot, and watershed scale toward a global system scale. In the 1980s, we rediscovered the 19th century understanding that all environmental and human systems are interlinked at different temporal and spatial scales (von Humboldt 1849). Ecologists like H.T. Odum (1983) and Holling (1986) provided much of the leadership and renewal of these ideas. In the 1990s, for the first time, we came to the realization that anthropogenic (cumulative) processes are quantitatively as pervasive as biogeochemical (systemic) processes in modifying our global environment (Turner et al. 1990; Vitousek et al. 1997). And finally in the 21st century, the rapid deployment of remote sensing systems and the computational capacity to store, manipulate, and present spatially referenced data have made the visual representation of complexly interacting human and biogeochemical systems more realistic and compelling.

The three major cryosphere regions of the world are Antarctica, the Arctic Ocean, and the extra-polar snow and mountain environments. Antarctica is a continent surrounded by ocean (Fig. 1.3). East Antarctica contains 77% of the Earth's ice by volume and West Antarctica contains 10%. A further

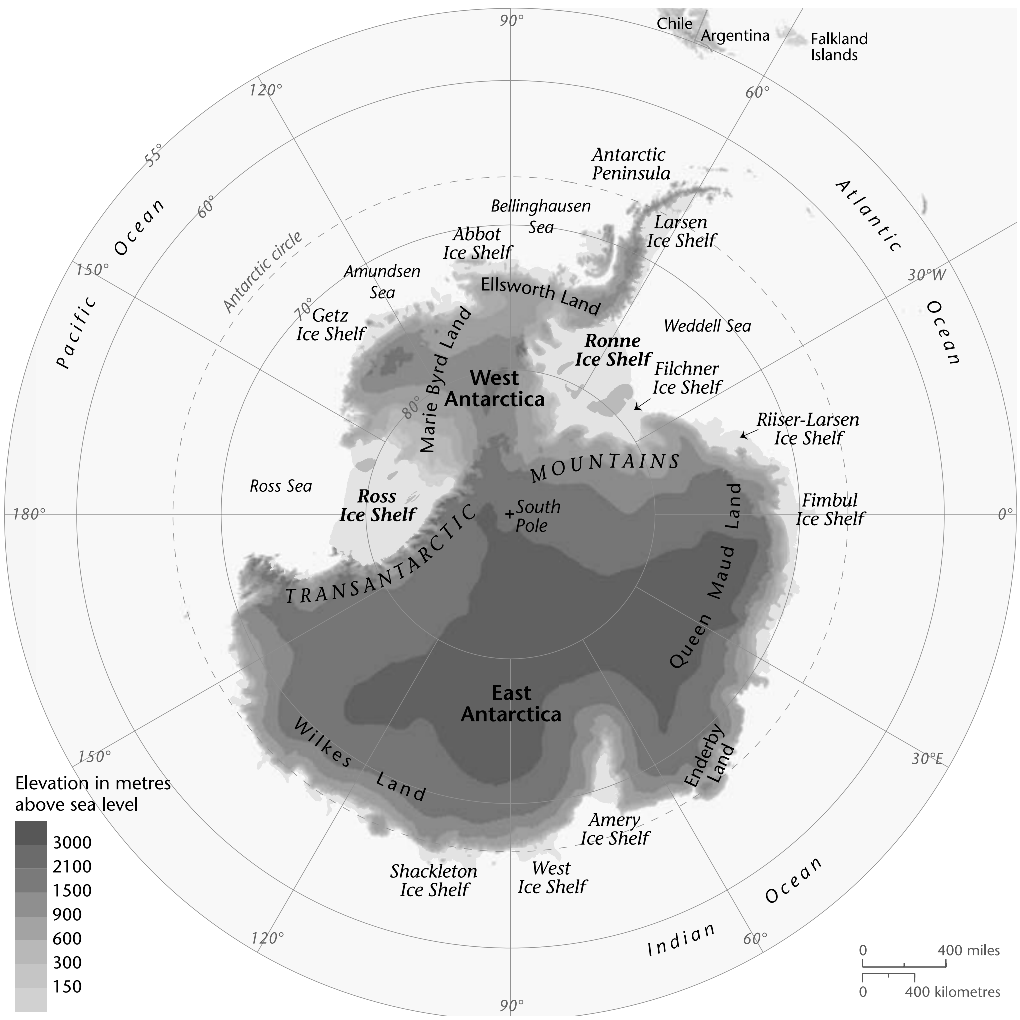

FIG. 1.3 The Antarctic cryosphere.

2.5% is found in the Antarctic ice shelves. The ice cover of Antarctica evolved in response to the opening of the Southern Ocean, first when it separated from Australia about 50 Ma but more dramatically when it finally separated from South America about 20–22 Ma. It is thought that East Antarctica has remained ice-covered throughout this period, including warmer episodes, such as the Pliocene (2–3 Ma). However, the West Antarctic Ice Sheet has probably decayed and regrown several times. In Chapter 5, we will return to this topic in more detail.

The Arctic (Fig. 1.4) is an ocean surrounded by land. Much of the surface consists of sea ice or pack ice, which circulates slowly in a clockwise direction, in response to underlying ocean currents. Most of the ice in the Arctic is contained in the Greenland Ice Sheet (9% of Earth's ice by volume) and in permafrost (0.9%). Less than 10% of Canada, Siberia, and northern Alaska is covered by glaciers and ice caps. Much of the ice-free terrain is underlain by permafrost.

The extra-polar regions (Fig. 1.5) contain only 0.5% of the Earth's ice and snow by volume. Yet, these small ice caps (Plate 1.1), mountain glaciers, snow, and alpine permafrost are extremely important in that their interaction with people is more intense than that in the circumpolar regions. Indeed, the fact that *c*.5.2 (10^7) km^2 of the extra-polar region is affected by seasonal frozen ground from time to time is a better index of the importance of the cryosphere in this region than the volumetric data. The case will be advanced in this book that, in the short- and medium term, changes of the cryosphere in the extra-polar regions are the most important ones to monitor, for at least two reasons: in these regions the cryosphere is closest to its threshold value and the anthropogenic impact is most pronounced.

We will first discuss the extra-polar cryosphere and potential effects on ocean circulation in the Arctic; then we will look at meltwater sources in the polar regions from the major ice sheets and the cumulative effect of these processes on global sea level changes and sea ice conditions; and finally we will look at major ecological impacts and some of the more urgent socioeconomic implications of cryosphere change.

1.2 The geomorphic and hydrologic effects of cryospheric change

The case for the importance of the climatic roles of snow and ice has been well and comprehensively documented. The case is made in two broad ways: first, in relation to the fundamental physical properties of snow and ice that modulate energy exchanges between the Earth's surface and the atmosphere (albedo, thermal diffusivity, and latent heat as well as surface roughness, emissivity, and dielectric characteristics) and second, in relation to the concept of residence time (flux/storage) of water within the cryosphere. Water with short residence times participates in the fast response regime of the climate system, whereas long residence time components act to modulate and introduce delays into the transient responses. Nevertheless the threat of abrupt changes in the slow response components must also be taken seriously.

The case for the importance of the geomorphic and hydrologic roles of snow and ice has also been comprehensively documented, but rarely with the same global sense as that of the climatic effects. The fact is that similar rationales can be provided for climatic, hydrologic, and geomorphic implications of cryospheric change. With respect to the fundamental physical properties of

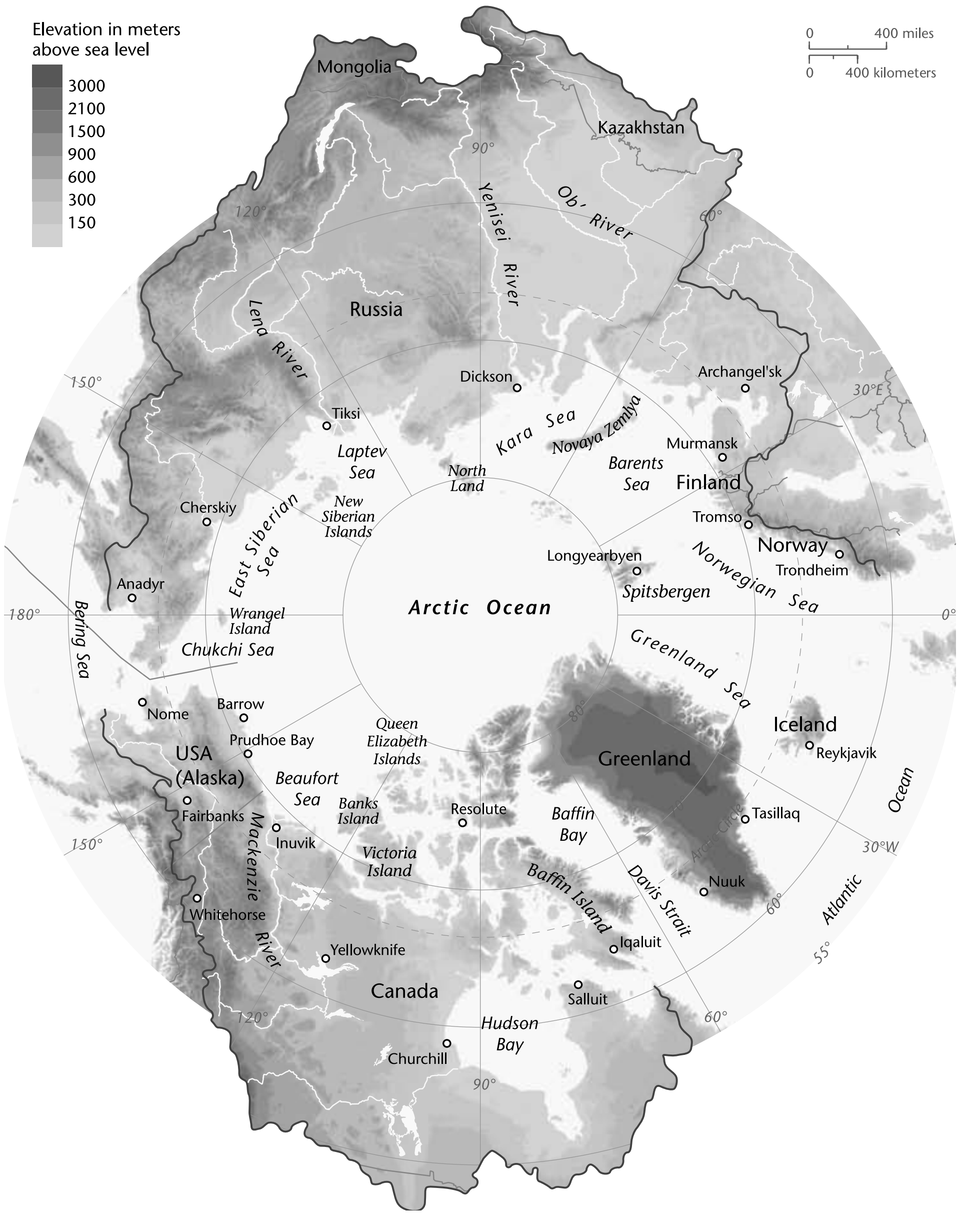

Fig. 1.4 The Arctic cryosphere, delineated by drainage basins of rivers tributary to Arctic Ocean.

snow and ice which affect hydrologic systems, it is for example, the strength, the crystal structure, the density, and the liquid water content of snow and ice that modulate both the mass and energy exchanges. In geomorphic terms, the mass exchanges of sediment are modulated by the ratio of the mean magnitude of barriers to change (lithology and available sediments) to the mean magnitudes of the disturbing forces (e.g. snowmelt runoff, jokulhlaups, or glacial erosional power) (Brunsden 1993).

Under the topic of residence times, the issue of flux to storage ratios has become a central topic, most recently sensitively discussed by Church (2002) in the context of the paraglacial concept. The distinctive characteristic of geomorphic systems is the way in which the storage term tends to dominate the mass balance. But by direct analogy with abrupt changes in the behavior of ice sheets, the history ofglacial/nonglacial alternating morphogenetic systems suggests that short periods of rapid change are separated by long periods of relative quiescence.

The practical importance of this point is that cryospheric change induced either by human activity or by climate can generate rapid landscape changes both at the local scale and, in a cumulative sense, at the global scale. The best documented example is the rapid change in discontinuous permafrost landscapes under the influence of infrastructure construction and/or progressive warming. But more dramatic are the effects of sandur landscape transformation under the influences of jokulhlaups in Iceland (Björnsson 2004) and elsewhere.

In a brilliant and compelling introduction to his book *Landscapes of Transition* (Hewitt et al. 2002), Hewitt has introduced the notion of "transition" to address the sense in which landscape development is not merely chronological and linear, or simply a "lagged" response to climatic and tectonic changes:

> *There are diachronous episodes of (incomplete) readjustment to the cessation of past conditions, and towards later conditions, of which those at present are only one set. There are distinctive spatial and temporal patterns of adjustment, including self adjustment specific to the earth surface processes at work. The paraglacial is a classic example. It is suggested that such temporal and spatial responses in earth surface processes apply much more generally as part of landscape transformation in the Quaternary. (Hewitt 2002, p. 2)*

We have found this seminal idea helpful in interpreting cryospheric change. There are parts of the cryosphere that are in incomplete transition from past conditions, notably the Antarctic and Greenland ice sheets and Siberian, Alaskan, and Canadian permafrost. At depth, these ice sheets and this permafrost are still responding to impetus from past extremes of cold, whereas at the surface they are driven by contemporary mass and energy budgets.

Few aspects of the landscape respond instantaneously to mass and energy inputs. Some aspects of the cryosphere, such as "wet snow," do, but the majority of the components of the cryosphere resists change until subjected to stresses sufficient to deform or remove them. In Chapter 6, we shall explore the implications of complex transitions of the cryosphere on the landscape.

1.3 Subarctic and alpine hydrology

The major Arctic rivers originate in more temperate latitudes, where human population densities are markedly greater than those within the Arctic region proper. The melting of glaciers in temperate alpine source areas, the changing regional hydrology of the subarctic, and the degradation of permafrost, especially in the discontinuous permafrost zone, will dominate the discharge regime of the major rivers. In addition, the land use impacts associated with accelerating resource development in the subarctic affect discharge and sediment transport regimes in medium-size basins.

Most developmental and industrial activities have a higher potential for producing significant pollution in the Arctic than in more temperate regions. Environmental sensitivity associated with freeze–thaw processes; the temperature-dependent rates of chemical and biological processes that degrade pollutants; and the fragility and low

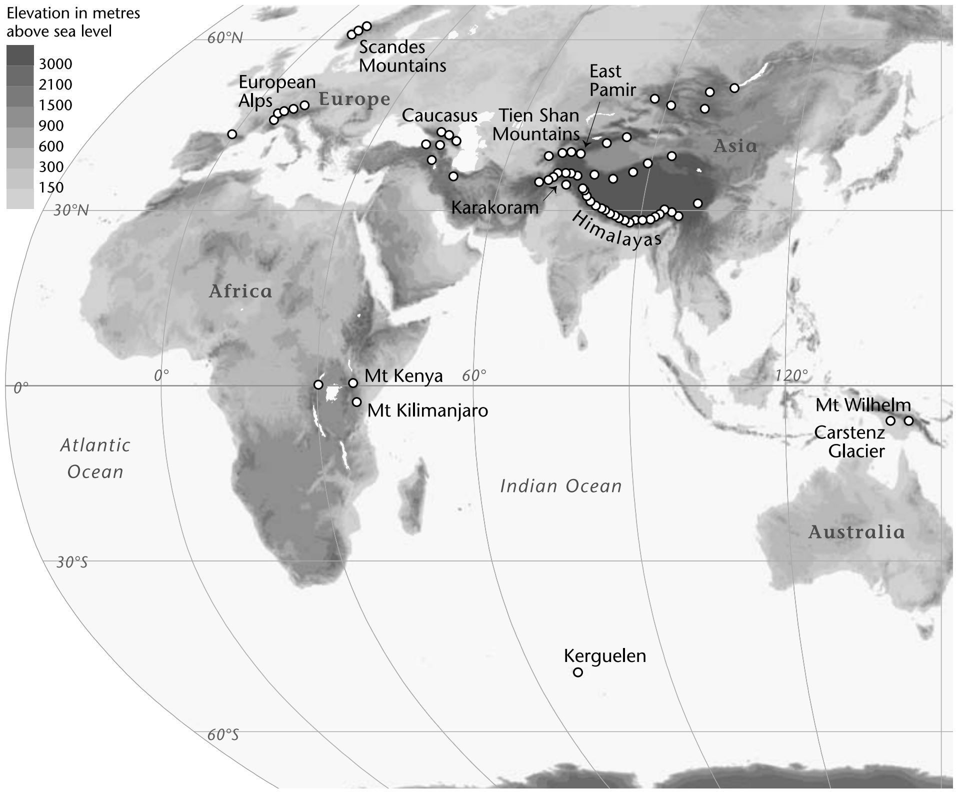

Fig. 1.5 The extra-polar cryosphere between the Arctic and Antarctic circles.

assimilative capacity of northern ecosystems may lead to cumulative and negative synergistic effects. Much pollution in the North originates from southerly latitudes and may be carried north not only by large river systems, but also by ocean currents and atmospheric processes (see Chapter 7).

The average rise in winter temperatures north of 60°N is expected to be 2–2.4 times the global average, resulting in temperature increases of 6–7°C at about 70°N (Roots 1990). Most warming is likely to occur in winter in continental locations, but only a small summer temperature increase of perhaps 1°C is anticipated. The zones of highest temperature increase should occur at the snow, ice/snow, and permafrost boundaries where the albedo changes dramatically.

Although evaporation rates may not change significantly, precipitation is expected to increase along the Arctic mainland coast and in the Arctic archipelagos up to fivefold (Roots 1990). The warmer conditions that are predicted for much of the circumpolar region will reduce the duration of winter. Seasonal snow accumulation could increase in higher-elevation zones and increased summer storminess may reduce melt at intermediate elevations as a result of increased cloudiness and summer snowfall (Woo 1996). At lower elevations, however, rainfall and rain-on-snow melt events will probably increase. There will be a shift from nival toward more pluvial runoff regimes.

Overall, present runoff to the Arctic Ocean is approximately twice that produced by precipitation minus evaporation over the Arctic Ocean. Of the total runoff to the Arctic Ocean, 70% is provided by the Ob, Yenisei, Lena, and Mackenzie rivers.

Models are predicting a total annual inflow increase to the Arctic Ocean of 10–20% with an atmospheric CO_2 doubling (Plate 1.2). Recent work on Siberian rivers emphasizes the importance of major dams, topography, and permafrost conditions in controlling discharge regimes. On the Ob and Yenisei rivers, winter snow accumulation influences summer and fall discharges whereas on the Lena River, which is further east, the winter and spring discharges are most affected (Ye et al. 2003).

The single most important point to note is that export of freshwater from the Arctic Ocean into the North Atlantic is the main coupling mechanism that links northern latitudes to the global thermohaline circulation (see Section 1.5). This export of freshwater seems very likely to increase under all scenarios modeled under a doubling of CO_2 assumption; this, as will be discussed later, will tend to reduce the intensity of that circulation, with potentially abrupt influence on the climate of the North Atlantic region.

1.4 Glacier loss and mountain permafrost

The estimated relative contribution to sea level rise that has been made by glaciers and small ice caps in the extra-polar regions over the past century is disproportionately large (Table 1.2). This is largely because the measurements of mass balances outside the polar regions are unambiguously negative, by contrast with the ambiguities of the mass balances of the major ice sheets. During the 20th century, there has been obvious thinning, mass loss, and retreat of mountain

TABLE 1.2 Estimated contributions to sea level rise over the last century in cm (from Warrick et al. 1996).

Component contributions	Low	Middle	High
Thermal expansion	2	4	7
Glaciers/small ice caps	2	3.5	5
Greenland Ice Sheet	−4	0	4
Antarctic Ice Sheet	−14	0	14
Surface water and ground water storage	−5	0.5	7
Total	−19	8	37
Observed	10	18	25

glaciers (Fig. 1.6). Nine regions (Fig. 1.6a) and nine individual glaciers with long historical records (Fig. 1.6b) demonstrate this trend and also show that such a trend will continue even if the present climatic regime were to continue unchanged. Doubling of CO_2 concentrations in the atmosphere is likely to lead to pronounced reductions in seasonal snow, permafrost, glacier, and periglacial belts of the world and a corresponding shift in landscape forming processes. Disappearance of up to 25% of presently existing mountain glacier mass is anticipated. Tropical alpine glaciers, especially those on Mount Kilimanjaro, have attracted serious concern. Increases in the thickness of the active layer of permafrost and the disappearance of extensive areas of discontinuous permafrost in mountain areas are also predicted. Borehole measurements in the European Alps (Haeberli et al. 2000) show that permafrost is warming in some areas but not everywhere.

More water will be released from regions with extensive glaciers. In temperate mountain regions, reduced duration of snow cover will cause moderation of the seasonal flow regime of rivers so that winter runoff increases and spring runoff decreases. Widespread loss of permafrost over mountain areas is expected to trigger accelerated mass movement, erosion, and sedimentation.

1.5 Permafrost

There is a long history of research experimentation on periglacial processes in the Arctic (Fig. 1.7).

Permafrost records temperature changes via the gradient of its subsurface temperature change with depth; it transmits these changes to other components of the environment and it facilitates further climate change by releasing trace gases. The physical expression of warming of the permafrost is the presence of thermokarst, a landscape of subsidence and highly unstable, spatially variable active layer. In unglaciated parts of Siberia, coalescing thaw depressions (known as alases), formed during Holocene warm intervals, occupy areas as large as 25 km^2. Frozen-ground activity has been designated as a "geoindicator" for monitoring and assessing environmental change (Berger & Iams 1996). It is critical to understand that ground ice content is highly spatially variable and that thaw settlement hazard is controlled by a combination of depth of thaw and ground ice content, not by the presence or absence of permafrost.

Permafrost regions represent 25% of the exposed land area of the northern hemisphere (Fig. 1.8). But because much of those regions is discontinuous permafrost, permafrost actually underlies 13–18% (Zhang et al. 2000). The interpretation of

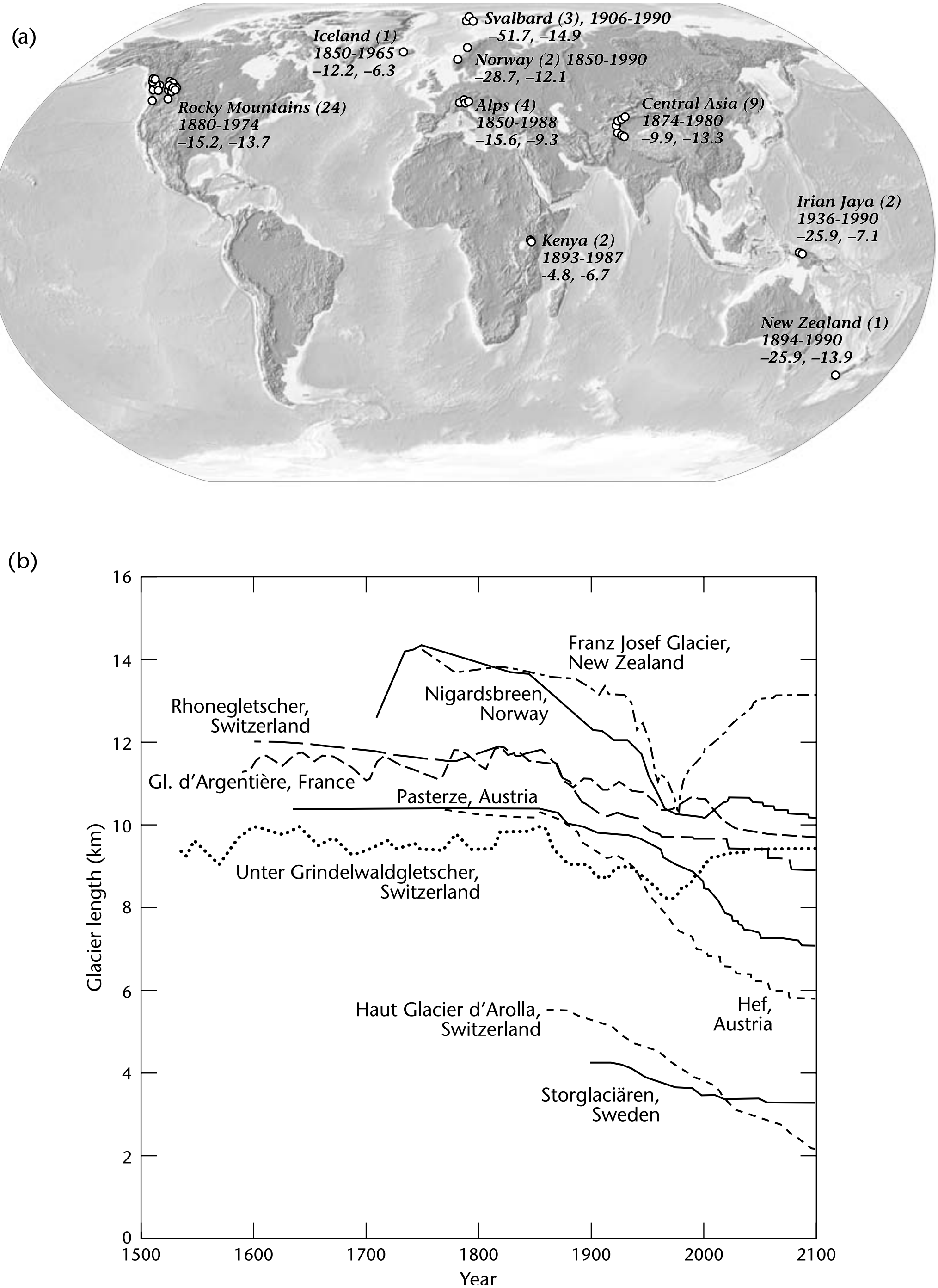

Fig. 1.6 (a) Results of an analysis of glacier length changes in km, summarized for nine regions. For each region are indicated the number of glaciers, the period of observations, the mean rate of retreat, and the mean scaled rate of retreat. The scaling effects maritime and low gradient glaciers differentially because of their greater sensitivity (after Oerlemans 2001). (b) Records of nine historic glacier lengths and projections into the future: Franz Josef Glacier (New Zealand); Glacier d'Argentière (France); Haut Glacier d'Arolla (Switzerland); Hintereisferner (Austria); Nigardsbreen (Norway); Pasterze (Austria); Rhonegletscher (Switzerland); Storglaciaren (Sweden); Unter Grindelwaldgletscher (Switzerland) (after Oerlemans 2001).

FIG. 1.7 The camp of the Polish research expedition in Arfersiorfik Fjord, West Greenland, just at the edge of ice sheet. July 1937 (photograph by the late Alfred Jahn).

these permafrost maps is a guide to those areas that are most susceptible to change as a result of predicted warming. Both thawing index and depth of permafrost are used to predict the level of hazard. It is anticipated that the area of continental permafrost may be reduced by 12–22% of its current extent under CO_2 doubling scenarios, and Smith and Burgess (1999) have predicted eventual disappearance of half of Canada's permafrost under such a scenario. The time lag involved in the thawing of thick permafrost may allow some relict permafrost to persist for millennia.

1.6 THE CARBON BALANCE OF THE CRYOSPHERE

A series of questions concerning the changing carbon balance resulting from melting permafrost and wetland hydrology under warming temperatures has arisen. In the Southern Ocean, it is projected that there will be a reduced uptake of GHGs. A coupled climate model estimate (Matear & Hirst 1999) suggests a reduced cumulative uptake by 2100 of 56 Gt. This is equivalent to a 4% a^{-1} increase in CO_2 emissions over the next century (Fig. 1.9). Whether the Arctic will be a net source or sink of CO_2 depends largely on the direction of hydrological change and the rate of decomposition of exposed peat in response to temperature change (McKane et al. 1997a, b). Tundra ecosystems have large stores of nutrients and carbon bound in permafrost, soil, and microbial biomass and have low rates of CO_2 uptake because of low net primary production (Callaghan & Jonasson 1995). The net effect of complex processes is the likelihood that GHG emissions will increase with warming temperatures.

It is also possible that natural gas will be released to the atmosphere as a result of destabilization of gas hydrates. In the northern seas, gas hydrates are sometimes deposited in the near-bottom zone and their decomposition is likely with a comparatively small increase in temperature. Methane hydrate destabilization has been documented during Quaternary interstadials (Kennett et al. 2000).

Predicting how northern peat carbon stocks may respond to a warming Arctic climate is a complex problem that remains intractable to date. One scenario is that warming will fuel an appreciable new CO_2 source, should currently frozen or waterlogged peats experience warmer temperatures, permafrost degradation, decreased water table elevation, and enhanced aerobic decomposition. Such fluxes are potentially large: Assuming no enhanced carbon uptake by the biosphere or ocean, complete oxidation of west Siberian peatlands over the next 500 years would release sufficient carbon to the atmosphere, so as to boost the present-day rate of atmospheric CO_2 increase by 4%. In terms of net greenhouse forcing, the warming effect of such a release would likely be offset by reduced methane emission but, even in the unlikely event of a total shutdown of methane emission, would still attain at least approximately 80% of its greenhouse warming potential. Evidence for a recent slowdown or stoppage in west