Mountain glaciers *face the* HEAT

The recognition of an error in the fourth assessment report of the Intergovernmental Panel on Climate Change put the spotlight on glaciers. Not all glaciers are about to disappear but their recession is real and so are the impacts the loss of this "stored water" will have on ecosystems and societies, **Ray Bradley** asserts.

The discovery in 1991 of a mummified body emerging from a melting ice field high in the Italian Alps was one of the most sensational archaeological findings of recent decades. "Ötzi" as he came to be known, together with his clothing and personal belongings, was preserved so well that studies of his remains claimed the attention of many scientists for two decades. The insights gained from these studies virtually rewrote what we know about early farming and herding life in the high mountains of southern Europe around 5 300 years BP (before present), a testimony to Ötzi's remarkable posthumous contributions to science.

Over recent years, many other well-preserved prehistoric artefacts have been recovered from melting snowfields on high mountain passes of the European Alps, and the western mountain ranges of North America. Hikers and climbers have found leather shoes and clothing, baskets, bows and arrows and other important samples of early technology, providing new insights into the lives of prehistoric hunter-gatherers in these remote mountain regions. But while melting snowfields and receding glaciers have proven to be a boon for archaeology, they also call attention to the magnitude of environmental changes taking place in mountain regions around the world. These changes have broad significance as they also affect the societies and ecosystems beyond the mountains that rely on mountain rivers and streams for their sustenance.

Glacier retreat is one of the most visible symbols of global warming.

Mountain glaciers and perennial snowfields comprise only a small fraction of the global cryosphere (the realm of snow and ice), accounting for about 100,000 km^3 of the 28 million km^3 of frozen water on Earth's landmasses. If all the glaciers and small ice caps outside of Greenland and Antarctica were to melt, global sea level would rise by just about a quarter of a metre. So on the face of it, mountain glaciers would seem to be relatively insignificant compared with the large ice sheets of Greenland and Antarctica. However, glaciers play a critically important role in the hydrology and river ecosystems of many regions, providing meltwater for drinking, irrigation, hydropower production and downstream river traffic.

Furthermore, unlike large ice sheets, glaciers respond relatively quickly to changes

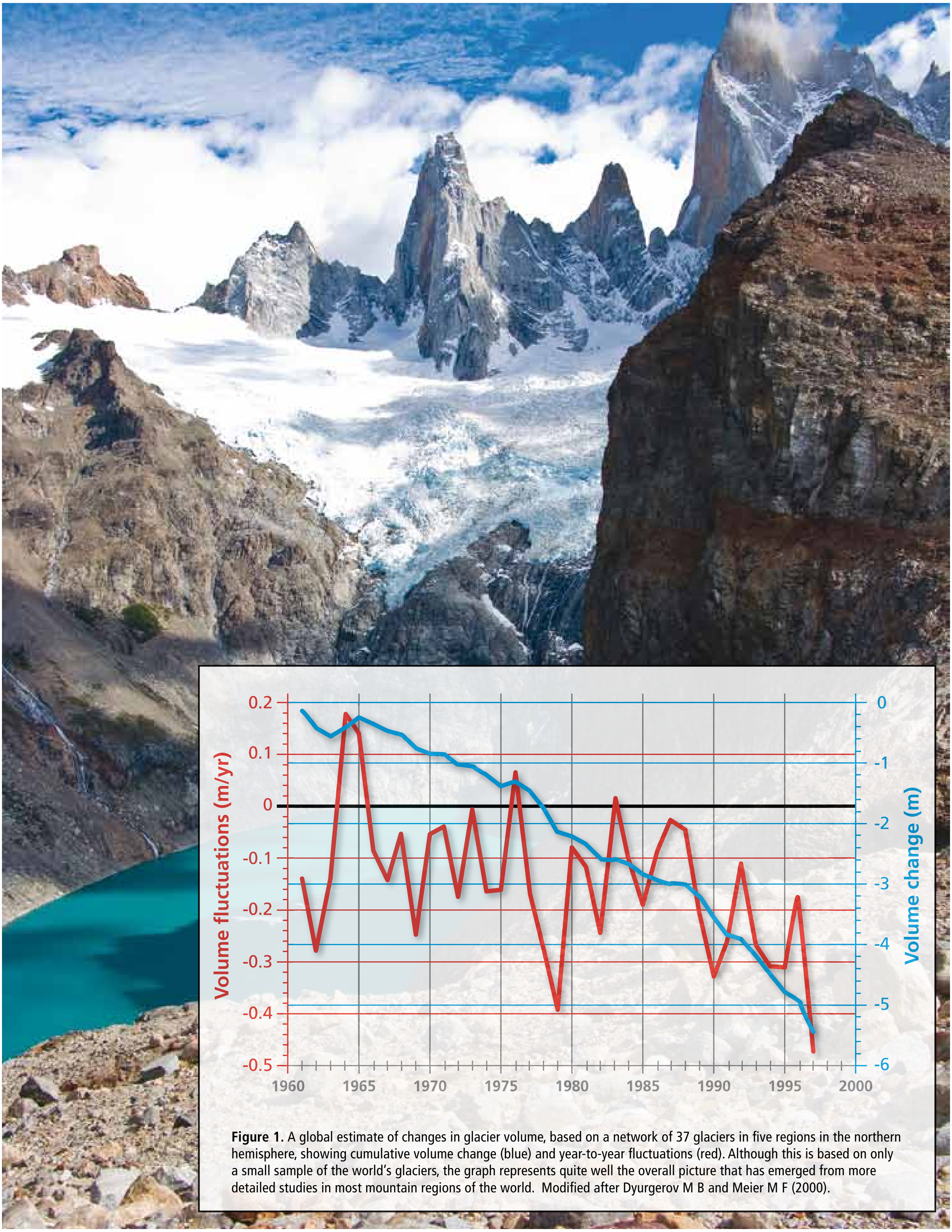

Figure 1. A global estimate of changes in glacier volume, based on a network of 37 glaciers in five regions in the northern hemisphere, showing cumulative volume change (blue) and year-to-year fluctuations (red). Although this is based on only a small sample of the world's glaciers, the graph represents quite well the overall picture that has emerged from more detailed studies in most mountain regions of the world. Modified after Dyurgerov M B and Meier M F (2000).

in climate (temperature and precipitation). Glaciers continually flow downhill. If the snowfall sustaining a glacier declines, or if there is an increase in ice loss (ablation), these will result in recession of the glacier or an overall thinning of the ice mass (or both), generally within a few years. So, as temperatures have risen almost all over the planet, the retreat of glaciers from mountain valleys is one of the most visible symbols of global warming. Rates of glacier recession vary from one region to another, and in a few areas glaciers have actually advanced in recent years. However, the overall picture of widespread recession is unequivocal (Figure 1) and reflects the familiar record of global warming. Where glaciers have bucked this trend, the explanation is generally due to regional circulation changes that have resulted in more winter snowfall, or to the fact that the retreat of some large glacier systems lags behind contemporary climate. This means that the recession of those glaciers is likely to be seen in future years.

Glacial meltwater has important ecological and economic value.

A tale of decline

In spite of sparse data for some regions, glaciers have been feeling the heat all over the world. Since 1850, the European Alps have seen glacier area plummet by 50 percent, with a corresponding 65 percent loss of ice volume. The rate of ice loss has accelerated significantly in the last 30 years. But this is still less than many high mountain regions of the tropics and subtropics. For example, between 1997 and 2008, Ecuador's glaciers lost 41 percent of their area. Between 1986 and 2000, northern Chile's glaciers declined by 40 percent. A recent study suggests that Columbia's glaciers may disappear in the coming two decades (Poveda and Piñeda 2009). In the mountains of East Africa and New Guinea, similarly high rates of ice loss have been recorded, and some high mountain ranges have become completely ice free. In a few cases, it is possible to place the magnitude of these changes in a long-term perspective.

In all likelihood, Ötzi had been ice-covered since he died in that remote location, 5 300 years ago. It is unlikely his body and fragile artefacts found with him would have survived exposure to the atmosphere. Similarly, leather artefacts found high on snowfields in the Swiss Alps, dating from 4900-4500 years BP, must have been buried in snow and ice throughout the intervening years. In Peru, plant material found beneath the receding edge of the Quelccaya Ice Cap (the largest ice cap in the tropics) was radiocarbon dated at ~5200 years BP. These and other studies suggest that the current recession of mountain glaciers and snowfields, across almost the entire globe, is greater than anything seen for many thousands of years, and provides support for the argument that anthropogenic effects on the climate system are unprecedented on the scale of recent human history.

Glacier recession is a symptom of global warming, and there is evidence that warming has been even greater at high elevations. In eastern Tibet, for example, the rate of warming over the last 50 years is two-to-three times greater above 4500 m than in areas below 1000 m. General circulation models used to assess the climate changes expected with increased levels of greenhouse gases show that high mountain regions in the tropics will experience higher temperatures than regions at lower elevations, and this may lead to a further decline in the extent of glaciers and perennial snowfields in those regions.

The glacial see-saw

During the last major ice age, about 21,000 years ago, vast ice sheets covered much of North America and Scandinavia, and sea-level was ~130 metres lower than it is today. As the position of the Earth in relation to the Sun changed, these ice sheets began melting and eventually disappeared almost completely around 6000 years ago, in the mid-Holocene period. Temperatures declined again in response to further changes in the Earth's orbital position, leading to a rejuvenation of glaciers in many mountain regions of the world during what is called the Neoglacial period. During the past few thousand years, glaciers have advanced and retreated in response to different factors – explosive volcanic eruptions occasionally cooling the Earth, changes in solar irradiance, changes in circulation patterns such as El Niños or other atmospheric modes and a host of local issues specific to different mountain ranges. From the 13th to the middle of the 19th century, a period dubbed "The Little Ice Age", mountain glaciers advanced throughout the world. Most scientists attribute this to a period of more frequent explosive volcanic eruptions, which reduced the amount of solar radiation reaching the Earth's surface.

Recently this pattern of glacier advances has abruptly shifted to one of widespread recession, as increased levels of greenhouse gases from fossil-fuel combustion overwhelmed natural factors, causing temperatures to rise to their highest level for over a thousand years. Today, in many mountain ranges, glaciers are disappearing, but the main polar ice sheets of Greenland and Antarctica remain. Nevertheless, even in those remote regions, evidence of glacier recession and ice-shelf collapse is growing, raising concerns about the stability of these vast ice masses and their potential to raise global sea-level significantly over the next century.

Global problem, regional twists

Glacial meltwater has important ecological and economic value, and any decrease is bound to affect downstream areas. But the specific impacts will likely vary based on location and context. Ecosystems and societies in parts of Central and South America are particularly vulnerable. A city like Lima in the dry coastal zone of Peru, for example, relies heavily on water that originates in the glaciated mountain ranges of the High Andes. In many countries in this region, run-off from glaciers is an important resource for hydropower generation. For example, 80 percent of electricity in Peru and 50 percent of electricity in Ecuador derives from hydropower. The World Bank estimates that the mean annual energy output from Peru's Cañon del Pato hydropower plant on the Rio Santa would drop from 1540 gigawatt-hours to 1250 gigawatt-hours with a 50 percent reduction in glacier run-off, and would be reduced further to 970 gigawatt-hours if the glacier run-off contribution disappeared completely.

Recent work (for example, Immerzeel *et al*. 2010; page 8 of this issue) suggests that the situation in Asia is more complex. Although there seems to be a general loss of ice in this region, some regions such as the Karakorum show an increase, and uncertainties about rates of change are considerable. Several major rivers – Indus, Ganges, Brahmaputra, Yangtze and Yellow – originate at high altitudes in the mountains of south-central Asia. But the relative contribution of meltwater (which includes glaciers as well as annual snowfall) and rainwater to each river basin varies.

In the lower Indus river valley, for example, much of the water for irrigation – which sustains a population of over 200 million people – comes from the high mountain glaciers and snowfields of the Himalayas. Similarly, meltwater amounts to about a quarter of the total discharge in the downstream areas of the Brahmaputra. For the other three rivers, the contribution is less than ten percent. Simulations by Immerzeel and colleagues suggest that the effect of climate change on water availability and food security in this region will be complex, with the Indus and Brahmaputra basins being severely affected and the Yellow River basin potentially benefiting.

Planning for the inevitable

To those with only a casual interest in the science of global warming, glacier recession may be the most visible expression of the complexity of environmental changes that are taking place throughout the Earth system. The loss of glaciers and upland snowfields certainly affects the aesthetics of mountain landscapes, and to many this effect by itself signals a tragic loss. But to millions of people living far from the mountains that provide life-sustaining water, the disappearance of glaciers will have a more profound significance and directly affect their way of life. As the above discussion suggests, there is a need for careful evaluation of region-specific response of the cryosphere to a changing climate and the impact this will have on societies and ecosystems.

Without policies to limit greenhouse gases and the associated relentless rise in global temperatures, the pattern of glacier recession is likely to continue. And even if mitigation policies were implemented today, nothing much can be done to save many glaciers. Some societies will thus need to adapt to these profound changes, and they will need all the help they can get from their governments and the international community.

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The need to assess the probable impacts of cryospheric changes in the mountain regions of the world has never been greater.

A good start would be to increase monitoring of environmental changes in the high mountains (particularly meteorological conditions at high elevations and hydrological regimes downstream from glaciers) and to evaluate potential hazards that may arise as glaciers recede. General circulation climate models, which are the normal tools used to simulate future climate, are of very limited value for mountainous regions where the topography is complex. High-resolution regional models and downscaling techniques are needed to obtain a more realistic picture. Such actions would be cost-effective investments that would support science-based planning to manage future changes that, at least in some parts of the world, now seem inevitable. ▮

RAYMOND BRADLEY, a member of IGBP's Scientific Committee, is Distinguished Professor in the Department of Geosciences, University of Massachusetts, Amherst, USA. Bradley leads an IGBP synthesis topic dealing with the impacts of cryospheric changes.
E-mail: rbradley@geo.umass.edu.

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