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The Cryosphere and Global Environmental Change: Some Geomorphic Perspectives.

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Abstract

A consideration of the global environmental changes affected by the cryosphere. The components of the terrestrial cryosphere (glaciers, snow, permafrost and lake and river ice) are analysed independently and also in the context of their influence on, and response to human activity in, large river basins tributary to the Arctic Ocean. Some of the geomorphic concepts that are thought to be important in interpreting these cryospheric changes are: thresholds, systems, complex response, resistance, panarchy, collapse and Yatsu's idea that "anything goes".

Key words: global environment, geomorphology, cryosphere

Introduction

Much has been written about systemic global environmental change, especially in the form of climate change and global warming (Houghton et al. 1990, 1996, 2001, Watson et al. 1996, McCarthy et al. 2001, Hassol 2004). The topic is important and has attracted the attention of policy and decision makers world wide. Systemic global environmental change is restricted to a consideration of global scale physically interconnected phenomena (Turner et al. 1990). It is a theme which tends to marginalize the potential role of much geomorphological research because it focuses on only one of the two major drivers of global environmental change, namely climate. The other major driver of global environmental change is human activity (Slaymaker 2000). Human activity affects land use and land cover at many discrete local and regional scales and produces global environmental change which is cumulative. The strength of this cumulative effect varies with the spatially variable resistance of Earth's surface properties, a theme which is familiar to geomorphologists. In this paper the focus is therefore on cumulative change. Nevertheless, our point of departure is the systemic signal of temperature and carbon dioxide concentration change in the atmosphere over the past 420,000 years (Petit et al. 1990) (Fig. 1). This strong correlation between carbon dioxide content in the atmosphere and temperature derives from the Vostok ice

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core in Antarctica and provides a framework for consideration of cryospheric change of particular relevance to geomorphology. Within that framework, the global cryosphere system is now, and has been throughout the Quaternary Period, dominated (in terms of volume) by ice sheets. But in terms of Earth's surface cover, ice sheets are relatively insignificant compared with snow and permafrost during the Northern hemisphere winter and compared with sea ice and permafrost during the Northern hemisphere summer (Fig. 2). The vast spatial extent of seasonal snow and permafrost is the scene of much



Fig. 1. Temperature and Carbon Dioxide concentration variations over the past 420,000 years from the Vostok ice core (modified from Petit et al. 1990).



Fig. 2. Ice sheets, permafrost, glaciers, lake and river ice, snow and sea ice as a percentage of the total cryosphere by (a) volume; (b) surface cover during Northern Hemisphere winter and (c) surface cover during Northern Hemisphere summer.

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geomorphic activity. In addition the sensitivity of extrapolar glaciers and of river and lake ice generates important loci for geomorphic process. Finally, and perhaps most importantly, the interaction of human activity with snow and ice is a subject of increasing importance; one with which geomorphologists have much experience. The purpose of this paper is to stimulate thinking about the actual and potential contribution of geomorphology to the global environmental change problematique (cf. Owens and Slaymaker 2004). Is our science really as irrelevant to global environmental change as is implied by the almost complete absence of its mention from the thousands of pages of the IPCC Reports?

In this paper we will consider some aspects of the geomorphic implications of permafrost, glaciers, river and lake ice and snow, as well as the integrated effects of human activity in river basins as cumulative contributors to global environmental change. We will also suggest some ways in which geomorphic concepts, developed in other environments, can be usefully employed in the interpretation of cryospheric change.

Elements of the terrestrial cryosphere

Permafrost

The 25 million km^2 of permafrost is of enormously varied thickness, and varies from continuous through discontinuous and sporadic to isolated patches of permafrost. Thickness varies from 1,600 m in the Yakutia region of Siberia to <1 m at the southern limit. Burn (1998) showed that the time scale for eradication of relatively thin permafrost (around 17 m thick) following natural disturbance in the discontinuous permafrost zone is on the order of centuries and millennia. This considerable persistence of permafrost following climatic change is due to latent heat contained in ground ice. Because all "warm" permafrost is a transient response to climate change, and because of the large number of compounding climatic variables, the prediction of precise changes is elusive. Cryostratigraphy of the last 20,000 years, such as that discussed by Murton and French (1993) and Fraser and Burn (1997), provides evidence of permafrost response to historical climate change.

Glaciers

Oerlemans (2001) has demonstrated the consistent reduction of glacier length since the Little Ice Age (1850–1990) from 48 glaciers located in 9 different regions (Fig. 3). The data were taken from the World Glacier Monitoring Service and were selected on the basis of having continuity of record from before 1940. All glaciers in the sample became shorter, the mean rates of retreat varying from 1.3–86 m/a. A scaling procedure was applied to accommodate the fact that maritime glaciers are more sensitive than continental ones and that low gradient glaciers are more sensitive than steep ones. The scaled retreat values had a significantly smaller variance than the calculated rates, especially because of the down-scaling of the very large absolute retreat rates from

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Svalbard and maritime Norway. The procedure is of great interest as it tends to emphasise the systemic response of glaciers. But from a geomorphic perspective, there is great interest in the spatially variable behaviour of the glaciers (Fig. 3) with Svalbard, Norway, New Zealand and Irian Jaya showing the highest absolute rates of retreat. It would have been instructive if comparable data from south-east Alaska, the most active sediment producing glaciers (Hallet et al. 1996), had been available.

River and lake ice

Assel et al. (1995) have demonstrated the reduction in ice cover time in the North American Great Lakes region from 1823–1994 (Fig. 4). The general timing of both freezeup and ice loss varies at the six sites studied. Freeze-up dates gradually became later and ice-loss dates gradually earlier from the start of records to the 1890's, marking the end of the Little Ice Age. Between the 1890's and the 1980's, the net effect was relatively constant. In the last decade of the record, earlier ice loss dates have been experienced. Indeed in the period 1983–92, Grand Traverse Bay, an arm of Lake Michigan did not freeze up in 6 of those 10 years, a record unique in the 144 years of observations. Once again, the broad systemic signal of longer periods of ice free lakes in the 1990's (as much as 30 days longer compared with the 1830's) is confirmed. From the geomorphic perspective, the different processes operating in the deeper water environments as compared with the shallow water protected environments is critical to the understanding of cumulative environmental change.

Under conditions of overall annual warming, the duration of river ice cover can be expected to be reduced. Many rivers within more temperate regions would tend to



Fig. 3. Mean rates and mean scaled rates of glacier length shortening (1850-1990) for all glaciers that have continuous records from before 1940 (modified from Oerlemans 2001).

become ice free, whereas in colder regions the present ice cover season could be shortened by as much as one month by the year 2050 (McCarthy et al. 2001). Warmer winters would cause more mid-winter break-ups as rapid snowmelt becomes more common. Warmer spring temperatures could affect the severity of the break-up, but the effect is the result of a complex balancing between downstream resistance (ice strength and thickness) and upstream forces (flood wave). Although thinner ice produced by a warmer winter would tend to promote a thermal break-up, this might be counteracted by the earlier timing of the event, reducing break-up severity (Prowse et al. 1990). Prowse (2000) has drawn attention to the highly variable local effects of changing freezeup and break-up dates of northern rivers on river ecology, especially on the conditions for salmon incubation in their gravel redds. Both ecological and geomorphic implications of intensification of the break-up floods are areas of needed research.

Snow

A decrease in spring snow extent over Eurasia has occurred since 1915 (McCarthy et al. 2001) and if global warming occurs, it is probable that precipitation in the circumpolar world will increase and snow fall in particular will increase. A number of general circulation models have predicted as much as a 35 % increase in precipitation in the Arctic over the next 100 years. Precipitation is expected to increase along the Arctic coast and archipelagos of Canada up to five-fold. The warmer conditions that are predicted for much of the circumpolar region will reduce the duration of winter. Seasonal snow accumulation could increase at higher elevation zones and increased summer



Fig. 4. Documented changes in freeze-up and break-up dates from long-term (1823-1994) ice records for the Laurentian lakes (modified from Assel et al. 1995).

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storminess may reduce melt at intermediate elevations; also increased cloudiness and summer snowfall at intermediate elevations complicate predictions (Woo 1996). At lower elevations however, rainfall and rain-on-snow events will probably increase. There will be a shift from nival towards more pluvial runoff regimes. Research into the hydrogeomorphology of nival regions, snow hydrology and effects of snowmelt on flood production are important to determine the cumulative impacts of changing snow regimes.

River basins

The major Arctic rivers, like the Yenisei, the Ob, and the Mackenzie, originate in more temperate latitudes, where population densities are markedly greater than those within the polar region. Land use impacts associated with accelerating resource development affect discharge and sediment discharge regimes (Yang et al. 2004a, Yang et al. 2004b). Present runoff to the Arctic Ocean is approximately twice that produced by precipitation minus evaporation for the Arctic Ocean (Berezovskaya et al. 2004). 70 % of the total runoff to the Arctic Ocean is provided by the Lena, Yenisei, Ob and Mackenzie rivers, which discharge nearly 2,000 km³ of water into the Arctic Ocean per annum (Fig. 5). Winter river discharge alone accounts for an increase of 100 km³ since 1940. Nevertheless, Woo and Thorne (2003) found no evidence of increased streamflow in the Mackenzie River, even though the break-up date for the mainstream Mackenzie has advanced about three days per decade in the last 30 years. Of the four large river basins tributary to the Arctic Ocean, the Lena has the smallest amount of human impact and provides the clearest signal of increasing discharge over the past 30 years (Yang et al. 2002, Ye et al. 2003).

The greatest socio-economic activity in the circumpolar world at the present time is in FSU. Not only is the environment modified by economic activity, but the economic activity is influenced by the presence of permafrost. Geomorphic and social impact assessments are much in demand (Ye et al. 2003).

Relevant geomorphic concepts

Thresholds

"Gilbert always thought in terms of equilibrium and ratios, particularly between force and resistance" (Chorley et al. 1964). This way of thinking led him to focus attention on thresholds, below which very little change was occurring and above which most of the geomorphic action took place. This has proved to be a fertile concept in fluvial geomorphology (especially Schumm 1977) and in many other branches of geomorphology. In lake and river ice studies, the freeze-up and break-up dates are obvious thresholds. In assessing the cumulative effects of large drainage basins on the Arctic Ocean one has to deal with thresholds for land use density that will affect the downstream behaviour; thresholds for the initiation of widespread movement of sediment and solutes; and thresholds with respect to the ability of the Arctic Ocean to absorb

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these effects.

Systems

The general systems way of thinking, as imported into geomorphology by Strahler (1952) and Chorley (1962), was intended to emphasise the interconnections between objects, their attributes and the processes which have formed them. Such thinking was by contrast with an emphasis on elements of the landscape, such as terraces and peneplain remnants which Chorley characterised as closed system thinking.



Fig. 5. The major Arctic river basins and their runoff contributions to the Arctic Ocean.

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Two papers by Mackay (1972, 1998) exemplify the systems approach to geocryology: in the first case an attempt to set permafrost processes into the larger context of the landscape, both above and below the ground; in the second case, one of the few examples of a field experiment in geomorphology applied to the understanding of a closed system pingo.

The analysis of river basins as systems can be traced back to Horton (1945). In the context of global environmental change it will become increasingly important to characterise the aggregate behaviour of large river basins, such as the Ob, the Yenisei, the Lena and the Mackenzie.

Complex Response

Complex response describes the way in which the internal structure of a system controls the reaction and relaxation of the system after disturbance or change (Brunsden 2004). The best illustrations derive from fluvial geomorphology (Schumm 1973 et seq.), but it seems probable that the cryosphere is replete with examples of complex responses. Perhaps the simplest example would come from the study of snowmelt in a cold snowpack. The precise timing and amount of snowmelt would then be regulated by the "cold content" of the snowpack. A more interesting example would be provided by the case of surging glaciers, in which the tendency for accelerated flow depends only in a minor sense on the mass and energy budgets because basal sliding appears to drive changes in glacier flow velocity and this in turn is driven by reorganization of the subglacial drainage system. Rising water pressures at the glacier bed, the presence of deformable sediment up-glacier and the internal thermal regime may also be critical (Clarke et al. 1984). The point at issue here is that the complexity of the response is determined by factors internal to the glacier system.

Resistance

Brunsden (1990) states that when a perturbation exceeds the resistance of the system, the system will react and relax toward a new stable state (Proposition 8). This whole process has been envisaged in three parts: time taken to react (reaction time); time taken to achieve a new characteristic state (relaxation time) and time during which this form exists (characteristic time or landform lifetime). If the interval between form changing events is shorter than the sum of reaction and relaxation times, there can be no characteristic form and in such circumstances all landforms are transient. The issue of transient states is central to the examination of sediment systems. Church and Slaymaker (1989) have claimed that Holocene time is inadequate to achieve an equilibrium response of sediment systems in British Columbia. This result has been reinforced for much of the rest of Canada (Church et al. 1999).

Collapse

The concept of an adaptive cycle (Holling 1986) has been viewed by many as a

successful way of looking at complexity, at the same time giving equal attention to environmental and socio-economic factors. In 2002, Gunderson and Holling proposed the term "panarchy" for a structure in which interacting systems of environment and society are inter-linked in adaptive cycles of growth, accumulation, collapse and renewal. These transformational cycles occur in nested sets at scales ranging from a snowpack to the whole cryosphere over periods from days to geological epochs. Although the term "cycle" is unpopular in geomorphology because of its long association with Davisian thinking the unique feature of the panarchy concept is the way in which it accommodates both growth and collapse. Jared Diamond (2005) has raised the question of what causes the collapse of cultures and civilizations. He discusses the progress and fate of six Viking experiments in establishing societies during the period 793-1368 A.D. and suggests that the success of the first three (Orkney, Shetland and Faeroe islands), the success with associated problems in Iceland; the failure of the Greenland Norse after 450 years and the Vinland colony, which was abandoned in its first decade have much to do with environmental differences between the colonies (Fig. 6). In geomorphic perspective, the growth and collapse of ice sheets with a 100,000 year frequency during the Quaternary Period provides an interesting analogue.

Anything Goes

In his latest monograph Yatsu (2002) has made an eloquent appeal to geomorphologists to avoid authoritarianism and to make geomorphology more scientific by following the injunction "anything goes". If I understand him correctly, he is urging



Fig. 6. The westward progression of Viking experiments in establishing societies in Orkney, Shetland, Faeroe, Iceland, Greenland and Vinland (modified from Diamond 2005).

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geomorphologists to not limit themselves to the traditional ideas of the subject but to range as broadly as possible with new concepts, methods and strategies. His injunction is particularly relevant if we, as geomorphologists, wish to make a greater impact on the cosmic problems of global environmental change. We need new concepts to make linkages between discrete temporal and spatial scales of analysis and to explore more rigorously the levels of uncertainty that are inherent in our attempts to think globally about cryospheric change.

Conclusion

Ideas such as panarchy from ecology and system collapse from cultural geography, as well as our traditional geomorphic concepts of thresholds, systems, complex response and geomorphic resistance, can enrich our understanding of the role of the cryosphere in global environmental change.

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