

## CLIMATE CHANGE AND EROSION PROCESSES IN MOUNTAIN REGIONS OF WESTERN CANADA

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**ABSTRACT** Five mountain regions of Western Canada display distinctive hydrologic regimes and can be expected to respond differently to climatic change. A review of the extreme boundary conditions for climate change by A.D. 2050 for western Canada between 50° and 60° North as simulated by global climatic models indicates that all predict warming and the majority predict increased precipitation. Implications of these predicted changes for erosion processes are shown to depend heavily on the lagged response to climate change of glacier, permafrost, vegetation, and sediment systems. While runoff and available water resources will respond to climate change on an annual basis, glacier, permafrost, and vegetation responses are measured in decades to centuries and sediment systems take centuries to millennia to respond regionally. The three sources of uncertainty (the spatial variability of mountain systems, the range of predicted climate change scenarios, and the variable lag times of environmental systems to climate change) lead to qualitative estimates and predictions of tendencies rather than to confident assertions about geomorphic impacts of climate change. If principles of sustainable development are to be applied to mountain systems over the next few decades, an improved understanding of climate-erosion relationships is urgently needed, in particular the relationship between relevant meteorological events and climate sensitive processes.

**RÉSUMÉ** *Les changements de climat et les processus d'érosion dans les régions montagneuses de l'ouest du Canada.* Cinq régions de l'ouest du Canada présentent des régimes hydrologiques particuliers, et sont donc susceptibles de répondre différemment à un changement de climat. Un examen des conditions limites extrêmes nécessaires pour un changement de climat avant l'an 2050 dans l'ouest du Canada, entre 50 et 60° de latitude Nord, sur la base de modèles climatiques globaux, indique que ces modèles prédisent tous un réchauffement et que la majorité d'entre eux prédisent une augmentation des précipitations. Cet article démontre que les implications de ces changements prévus, en ce qui concerne les processus d'érosion, dépendent énormément de la réponse retardée à un changement de climat des systèmes glacier, pergélisol, végétation et sédiment. Alors que le ruissellement et les ressources en eau disponibles répondent à un changement de climat à l'échelle d'une année, la réponse des systèmes glacier, pergélisol et végétation est mesurée en termes de dizaines à centaines d'années, et celle du système sédiment s'étend de centaines à milliers d'années au niveau d'une région. Les trois sources d'incertitude (la variabilité spatiale des systèmes montagnards, la plage des scénarios de changement de climat, et les temps de retard variables des systèmes environnementaux vis-à-vis d'un changement de climat) conduisent à des estimations qualitatives et des prédictions de tendances plutôt qu'à des affirmations sûres au sujet des impacts géomorphiques d'un changement de climat. Si, au cours des prochaines décennies, on désire appliquer les principes du développement soutenable aux systèmes montagnards, une meilleure compréhension de la relation entre le climat et l'érosion est à présent indispensable, en particulier la relation entre les événements météorologiques significatifs et les processus sensibles au climat.

**ZUSAMMENFASSUNG** *Klimatische Veränderung und Erosionsprozesse in Gebirgsregionen des westlichen Kanada.* Im Westen Kanadas zeigen fünf Gebirgsregionen ausgeprägte hydrologische Systeme, die erwartungsgemäß unterschiedlich auf klimatische Veränderungen reagieren. Eine Überprüfung der extremen Grenzbedingungen für Klimaveränderungen bis zum Jahr 2050 für das westliche Kanada zwischen 50° und 60° N, wie es durch globale Klimamodelle simuliert wird, zeigt, daß alle Modelle eine Erwärmung und die Mehrzahl erhöhte Niederschläge vorhersagen. Die Bedeutung dieser durch Klimaschwankungen vorhergesagten Änderungen für Erosionsvorgänge hängt in starkem Maß von der zeitlich verzögerten Reaktion der Gletscher, des Permafrosts, der Vegetation und der Sedimentsysteme auf Klimaveränderungen ab. Abflüsse und vorhandene Wasserressourcen werden auf klimatische Veränderungen in jährlichem Zyklus reagieren; die Reaktion der Gletscher, des Permafrosts und der Vegetation wird dagegen in Dekaden oder Jahrhunderten gemessen; die Sedimentsysteme brauchen Jahrhunderte bis Jahrtausende, um regionale Veränderungen zu zeigen. Drei Unsicherheitsfaktoren (die räumliche Verschiedenheit der Gebirgssysteme, der Spielraum der vorhergesagten Klimaänderungen und unterschiedliche zeitliche Verzögerung der Umweltsysteme auf Klimaveränderungen) erlauben nur qualitative Schätzungen und Vorhersagen von möglichen Tendenzen im Gegensatz zu gesicherten Aussagen über geomorphische Auswirkungen der Klimaveränderungen. Wenn über die nächsten Jahrzehnte die Grundregeln kontinuierlicher Entwicklung auf Gebirgssysteme angewendet werden sollen, ist ein besseres Verständnis der Beziehungen zwischen Klima und Erosion unbedingt erforderlich, insbesondere solcher zwischen relevanten, meteorologischen Ereignissen und klimaabhängigen Vorgängen.

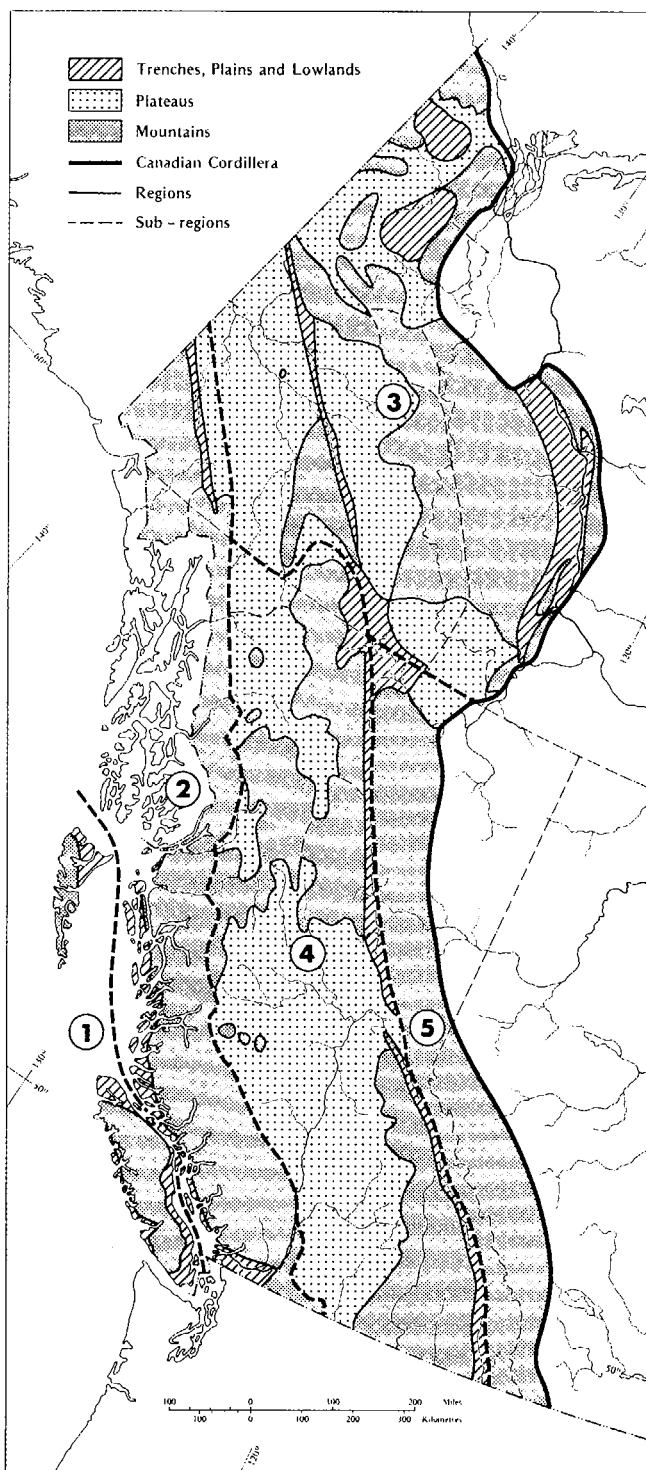


FIGURE 1. Western Canada's mountain regions.

1. Insular Mountains
2. St. Elias and Coastal Mountains
3. Subarctic Dry Interior Mountains
4. Temperate Interior Alpine Mountains
5. Temperate Dry Interior Mountains

The effects of anticipated climate change on erosion processes in mountain regions are poorly understood. The incidence of climate-induced natural hazards and the carrying capacity of mountain lands will surely change, but precisely how we do not know. If principles of sustainable development are to be applied in mountain land management then there is some urgency in investigating this problem. The problem consists of four parts:

1. What is the spatial variability of mountain climates?
2. What is predicted about climate change over the next 60 years and its hydrologic effects?
3. What is known about the relationship between climate and erosion processes in mountains?
4. What are the probable geomorphic impacts of climate change in specific mountain regions?

These questions are addressed with specific reference to the mountains of Western Canada, with which the author has greatest familiarity.

The major background problem is uncertainty over the time required for climate change and environmental sys-

TABLE 1  
Mean annual water balances for five mountain regions (1979-1989)

	P (mm)	= Q (mm)	+ ET (mm)	- S (mm)
Insular mountains	4,000	= 3,500	+ 500	
Coast mountains	3,500	= 3,150	+ 500	- 150
Subarctic interior mountains	300	= 200	+ 100	
Alpine interior mountains	1,200	= 700	+ 500	
Dry interior (Rocky) mountains	800	= 400	+ 400	
Regional	1,450	= 1,120	+ 365	- 35

TABLE 2  
Distribution of runoff by season for five mountain regions

	Q (mm)	Q <sub>w</sub> (mm)		Q <sub>s</sub> (mm)	
		Nov.-Apr. Winter	%	May-Oct. Summer	%
Insular mountains					
Somass	3,160	2,054	65	1,106	35
Pallant	4,240	2,756	65	1,484	35
Coast mountains					
Seymour	3,000	1,740	58	1,260	42
Squamish	3,320	764	23	2,556	77
Subarctic interior mountains					
Pelly	330	26	8	304	92
Alpine interior mountains					
Quesnel	720	144	20	576	80
Dry interior (Rocky) mountains					
Kootenay	490	78	16	412	84

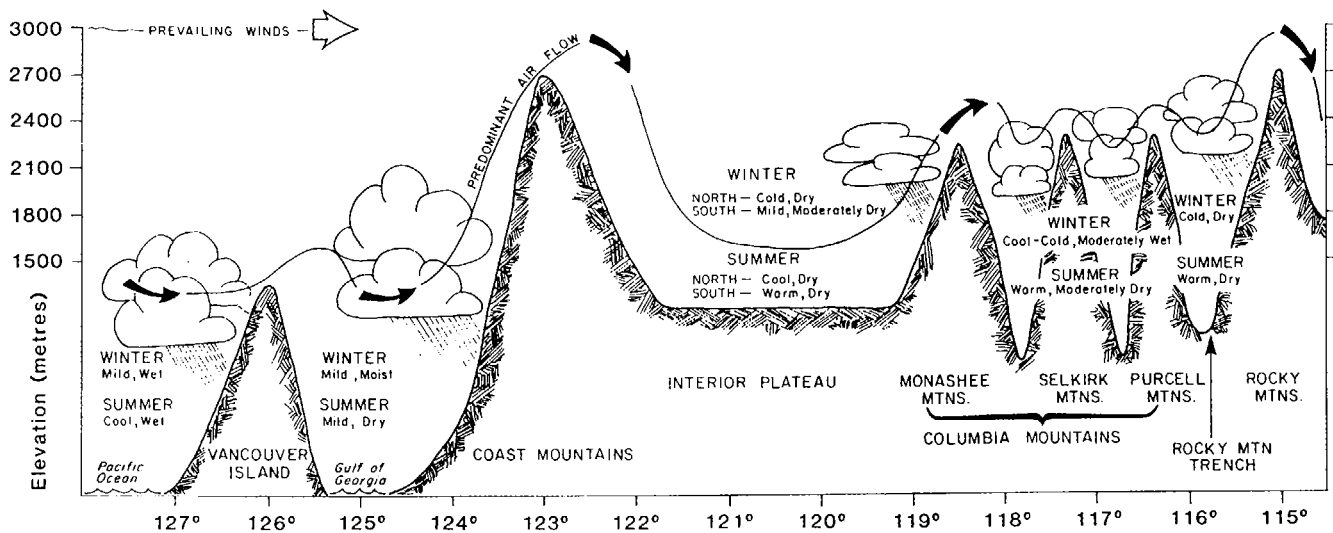


FIGURE 2. Latitudinal cross-section of southern British Columbia (after Chilton, 1981).

TABLE 3  
 Representative runoff data for five mountain regions

	Area (km <sup>2</sup> )	Records since	Complete years	Q m <sup>3</sup> sec <sup>-1</sup>	Q <sub>i</sub> m <sup>3</sup> sec <sup>-1</sup> km <sup>-2</sup>	Peak Q m <sup>3</sup> sec <sup>-1</sup>	Peak Q m <sup>3</sup> sec <sup>-1</sup> km <sup>-2</sup>
Insular mountains							
Pallant	78.7	1963	13	8.11	0.130	93.4	1.19
Gold	1,010	1956	25	83.4	0.082	1,890	1.87
Somass	1,280	1958	27	124	0.097	1,130	0.90
Coast mountains							
Exchamsiks	370	1962	22	42.2	0.114	572	1.55
Seymour	176	1929	58	16.2	0.092	430	2.45
Lillooet	2,160	1914	62	125	0.058	1,310	0.61
Squamish	2,330	1923	26	238	0.102	2,230	0.96
Subarctic interior mountains							
Pelly	18,400	1954	15	187	0.010	2,010	0.11
Alpine interior mountains							
Quesnel	5,930	1924	53	129	0.022	606	0.10
Dry interior (Rocky) mountains							
Kootenay	13,600	1914	54	205	0.015	1,820	0.13
River basins in more than one hydrologic region							
Fraser	217,000	1912	75	2,725	0.013	15,200	0.07
Skeena	42,200	1928	45	912	0.022	8,100	0.19
Stikine	29,300	1954	23	405	0.014	3,400	0.12
Homathko	5,720	1957	19	265	0.046	3,140	0.55

tems to achieve an equilibrium adjustment. Many changes that we monitor and observe are transient and not equilibrium responses. In connection with the phenomenon of climate change itself, observed changes are a function of the thermal inertia of the ocean, climate sensitivity, and the rate of change of the forcing function. Erosion processes which are commonly threshold exceedance related are rarely equilibrium responses to climate change; yet we do not know how long it will take for an equilibrium response to be established in a given case.

In addition to the complexity of the temporal response pattern, the spatial variability of mountain regions is high. The first task is therefore to identify the broad spatial patterns of the Canadian Cordilleran region.

#### 1. CANADA'S WESTERN MOUNTAIN REGIONS

In Western Canada's mountains, regional variations are substantial. It is anticipated that climate change will produce a somewhat different response in each region. At least five distinct hydrologic regions, whose mean annual water

balances differ markedly, can be recognized. They are the Insular Mountains, the Coast Mountains, the Subarctic Interior Mountains, the Alpine Interior Mountains, and the Dry Interior Mountains (Figure 1). Finer spatial resolution is, of course, possible but for present discussion more detailed regionalization would be counterproductive. Tables 1, 2, and 3 provide representative water balance and runoff data for the five regions.

#### a. The Insular Mountains

The perhumid Insular Mountains of Vancouver Island and the Queen Charlotte Islands cover 27,000 km<sup>2</sup> and experience a high rainfall (Figures 1 and 2). The mean annual precipitation is greater than 4,000 mm, of which only 2% falls in the form of snow. Mean annual temperature at sea level is +8.5°C and regional runoff is estimated at 3,500 mm (or 0.11 m<sup>3</sup> sec<sup>-1</sup> km<sup>-2</sup>). Of this total, 64% runs off in the winter months. Rainfall and rain-on-snow events are the common cause of peak runoff in winter and the runoff regime parallels the precipitation regime. In all other mountain regions of the Cordillera snow storage effects dominate the runoff regime.

#### b. Coast Mountains

This is a region of 193,000 km<sup>2</sup> which experiences a high precipitation, high snowfall, high runoff, and has a mean annual temperature at sea level of +5 to +8°C. The regional runoff averages 3,150 mm (or 0.10 m<sup>3</sup> sec<sup>-1</sup> km<sup>-2</sup>). Of this total, only 30% runs off in the winter months. Glacier melt contributes at least 5% annually to the runoff. Rain-on-snow events are the common cause of peak runoff.

#### c. Subarctic Interior Mountains

The Subarctic Interior Mountains cover 243,000 km<sup>2</sup> and can be represented by Dawson, Yukon Territory. Dawson has a mean annual precipitation of 300 mm, of which 46% falls as snow, and a mean annual temperature of -4.5°C at 369 m above sea level. Runoff for the region averages 0.006 m<sup>3</sup> sec<sup>-1</sup> km<sup>-2</sup> (or 200 mm), of which 8% runs off in the winter months.

#### d. Alpine Interior Mountains

Temperate interior alpine mountains cover 223,000 km<sup>2</sup> and can be represented by Mt. Fidelity which has 2,300 mm of precipitation (of which 78% falls as snow). Mt. Fidelity has a mean annual temperature of 0°C at 1,875 m a.s.l. The average runoff is 700 mm (or 0.021 m<sup>3</sup> sec<sup>-1</sup> km<sup>-2</sup>) with a range of 460 mm in the Cassiar Mountains to 980 mm in the Columbia Mountains. Twenty percent runs off in the winter months. Snowmelt accounts for annual peak runoff events.

#### e. Dry Interior Mountains

This is the Rocky Mountain region which covers about 176,000 km<sup>2</sup>. These temperate dry interior mountains can be represented by Banff, which has a mean annual precipitation of 460 mm, of which 44% falls in the form of snow, and a mean annual temperature of +1.5°C at 1,397 m a.s.l. Runoff for the region averages 0.012 m<sup>3</sup> sec<sup>-1</sup> km<sup>-2</sup> (or 400 mm). Only 16% runs off in the winter months. Snowmelt accounts for annual peak runoff events.

## 2. CLIMATE CHANGE OVER THE NEXT SIXTY YEARS AND ITS HYDROLOGIC EFFECTS

"Climate warming will probably result in a rise in the near surface temperature of the Earth of 1.5 to 4.5°C. At high latitudes the warming may be twice the global average. Also the warming will be accompanied by changes in the amount and distribution of rainfall" (Ferguson, 1988). There is disagreement on the extent of these changes, and accurate regional and seasonal information necessary to assess impacts is lacking.

Output from General Circulation Models (GCMs) can be used to provide boundary conditions for scenarios developed for Western Canada. Five groups have published results of simulations of the global climate under conditions of doubled atmospheric concentration of CO<sub>2</sub> by A.D. 2050 (McBean *et al.*, in press). Equilibrium doubled CO<sub>2</sub> warmings for the 50–60° North latitude band were assessed to be 7°C for winter and 4°C for summer, both with an uncertainty of 3°C. In the winter, coastal areas will be warmed 1–2°C less due to the oceanic influence. Because the warming will lag the increase in CO<sub>2</sub>, these values should be multiplied by 0.6 for the warming in 2050, the year of assumed CO<sub>2</sub> doubling. The winter time precipitation increase is estimated at 100 mm and larger increases are likely along the coast. In summer, the changes will be smaller and could be negative in the interior of British Columbia. The uncertainty for changes in precipitation is larger than that for temperature. Extreme boundary conditions that are predicted from the GCMs for Western Canada (50–60°N) can be summarized as follows:

#### (i) Warmest and driest scenario

Winter temperature +6°C and summer temperature +4.2°C. Winter precipitation no change and summer temperature no change (possible decrease in semi-arid interior).

#### (ii) Coolest and wettest scenario

Winter temperature +2.4°C and summer temperature +0.6°C. Winter precipitation +200 mm and summer precipitation +100 mm.

All scenarios predict warming; the majority also predict increased precipitation. More extreme predictions on warming for the 60–70° North zone, including Yukon Territory, are available. Implications of such changes are considered below.

The complexity of climate change effects on river runoff can be emphasized by reviewing the ways in which precipitation and temperature regulate the hydrologic cycle (Figure 3). The primary input of precipitation is regulated by the regional thermal climate such that temporary snow or ice storage may occur. The local thermal climate determines the precise nature of the snow and/or ice storage. If temperatures are above freezing, the infiltration capacity of the surface materials regulates water movement either to soil moisture or groundwater storage or as direct runoff. In turn, soil moisture storage capacity regulates contributions of soil moisture to delayed runoff. At the same time the ground thermal climate regulates ground ice occurrence and storage and the local thermal climate regulates evaporation and transpiration. Runoff is stored in lakes, bogs, and channels at which point regional thermal

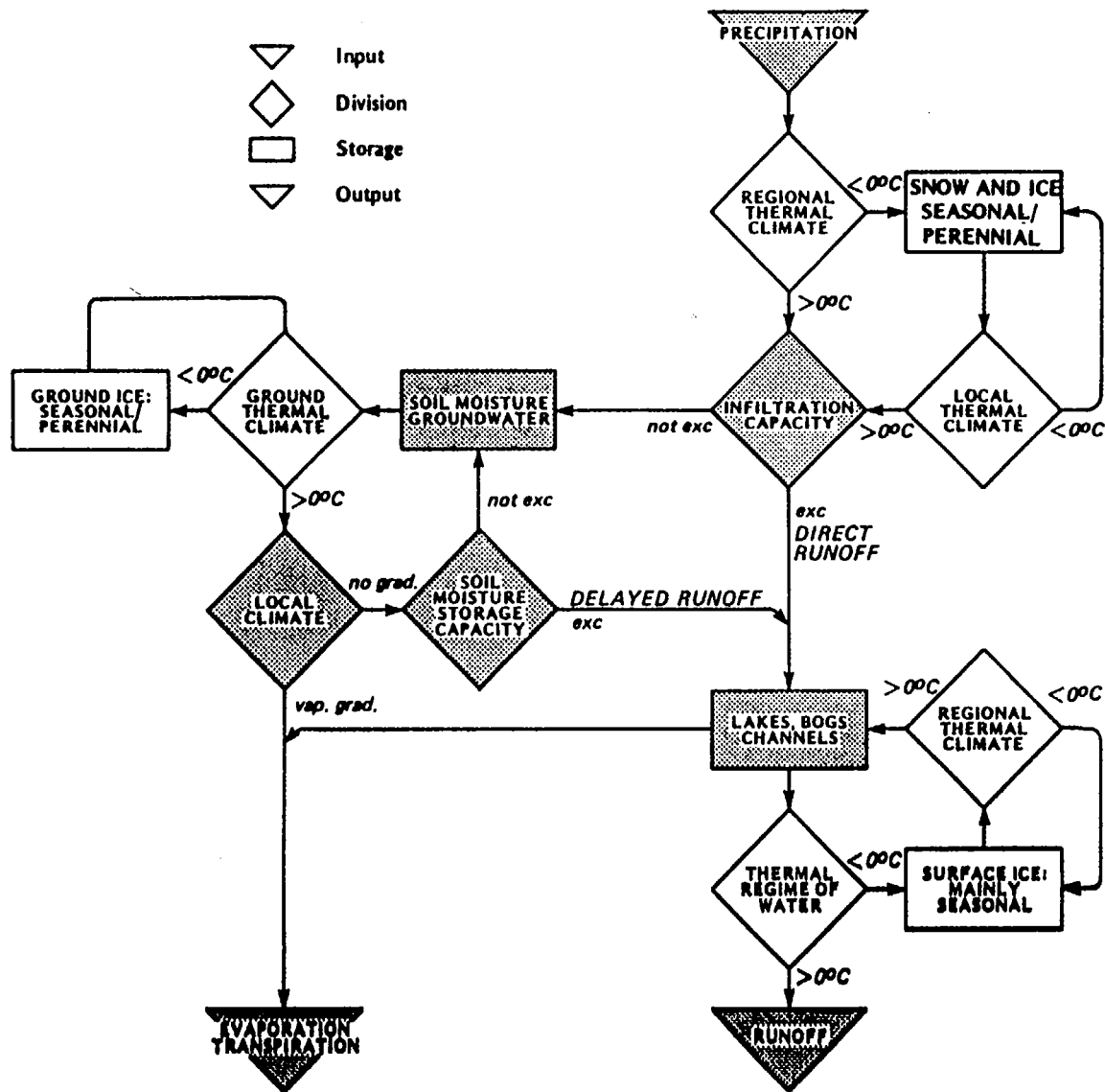


FIGURE 3. Terrestrial hydrologic cycle in the nival region (after Church, 1988).

climate and thermal regime of water regulates the surface ice storage. Finally, water above the freezing point runs off.

In Canada's Cordilleran region, because of the effects of altitude, relief, and the wide variety of surface materials, the full range of water pathways and storage zones can be found. Snow, soil moisture, lake, bog, channel, and surface ice storages are important at time scales of less than one year. Glacier ice and groundwater storage occur over longer periods. In the region under study, lacking any evidence of systematic regional drawdown of groundwater tables, glacier ice is the major storage problem.

There is a great variety of models available for prediction of hydrologic effects of climate change. In general, some variant of the Thornthwaite-Mather (1955) water balance method would seem essential down to the monthly time scale, in spite of, and in full recognition of, the difficulties associated with evapotranspiration and groundwater

recharge calculations (Alley, 1984). There is a revival of interest in water balance models, partly because of their compatibility with the scale of output from GCMs but also, and more importantly, because of an increasing recognition that the unravelling of the water balance equation at several scales is the essential task of the hydrologic scientist. Gleick (1986) presented the rationale for the compatibility of GCMs and water balance modeling and their value in predicting hydrologic effects of climate change. The advantages perceived over all other classes of models are identified as accuracy, flexibility, and ease of use with respect both to hydrologic consequences of climate change and to the ability to incorporate month-to-month and seasonal variations.

So-called conceptual runoff models are also increasingly important and improved analysis of the distribution of runoff, evapotranspiration, and precipitation data for given

TABLE 4  
Hydrologic effects of climatic change

Hydrologic Variable of Interest
Precipitation
Surface runoff
Snow cover
Glacier ice
Available soil moisture
Groundwater
Evapotranspiration
Storm events (magnitude, frequency, duration)
Temporal Scale of Interest
Long-term (greater than annual)
Annual
Seasonal (two-to-six months)
Short-term
Spatial Scale of Interest
Regional $10^5$ - $10^6$ km <sup>2</sup>
Watershed $10^2$ - $10^5$ km <sup>2</sup>
Statistics of Interest
Mean
Variance
Persistence
Hydrologic Impact of Interest
Quantity
Quality
Peak events (high and low)
Freshet flows

regions and their inherent variability is urgently needed (Solomon *et al.*, 1987).

Many engineering designs depend on the concept of probable maximum precipitation and probable maximum flood. Because a temperature increase of 1°C increases the saturation vapor pressure over the sea about 10%, total atmospheric moisture and total precipitation could increase and individual storm precipitation could be expected to increase (Clark, 1987). The problem with this approach is the whole concept of a probable maximum flood, as indicated in the recent discussion by Klemes (1988).

It is useful to solve the general water balance equation for the region and, secondly, to consider how each of the components of that water balance will be affected by climatic change. A checklist of the variety of hydrologic effects of climatic change is included (Table 4) because it is clear that the parameters that are most readily available are not necessarily the most informative.

#### Runoff Response

Barrett (1979) established that runoff changes in British Columbian rivers over the period 1913-77 were broadly controlled by precipitation changes (Figure 4) and that in the majority of cases the effect was evident in the same year as the precipitation change. By analyzing cumulative departures from the mean he showed that the average discharge of most of British Columbia's rivers increased by about 20% in the mid-1940s and remained at this level for about 30 years. An increase in precipitation, mainly dur-

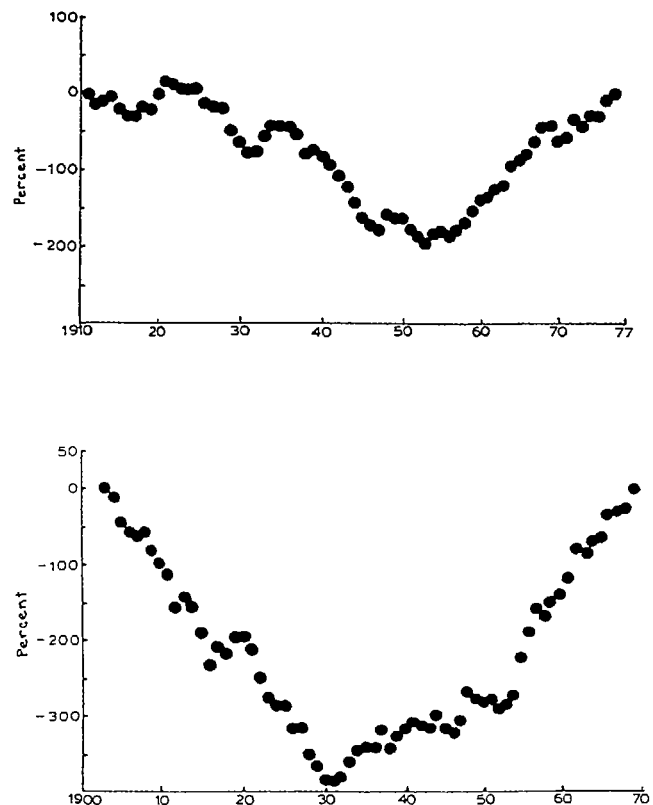


FIGURE 4. Cumulative percentage departures from the mean for: Upper: Fraser River at Hope, annual discharge, Lower: Quesnel, precipitation (Barrett, 1979).

ing the winter months, was held to be responsible. The only exceptions were heavily glacierized basins and basins in the semi-arid southern Interior Plateau.

#### Glacier Response

The surface runoff response to climate change, though complex, is relatively direct; lag times are of the order of one year or less. Glaciers, however, show a response to climate change which is lagged. Luckman (this issue, pp. 183-195) reviews glacier records for the Canadian Rockies, but acknowledges that the resolution is inadequate to determine lag time. On the other hand, the broad trend in the glacier mass balance records provides one of the clearest signals of climatic trends over the last century. Meier (1983) and Kuhn (1985) have discussed the nonlinearities in the climate glacier runoff system and the uncertainties involved in predicting glacier response to climate change. As explained by Paterson (1981), the response of a glacier to changes in mass balance involves time lags of tens-to-hundreds of years. In those cases where adequate records are available, namely Berendon Glacier in the Coast Mountains of British Columbia, South Cascade Glacier in the Washington Cascade Mountains, and Storglaciaren in Sweden, the time lags are 50, 42, and 56 years, respectively.

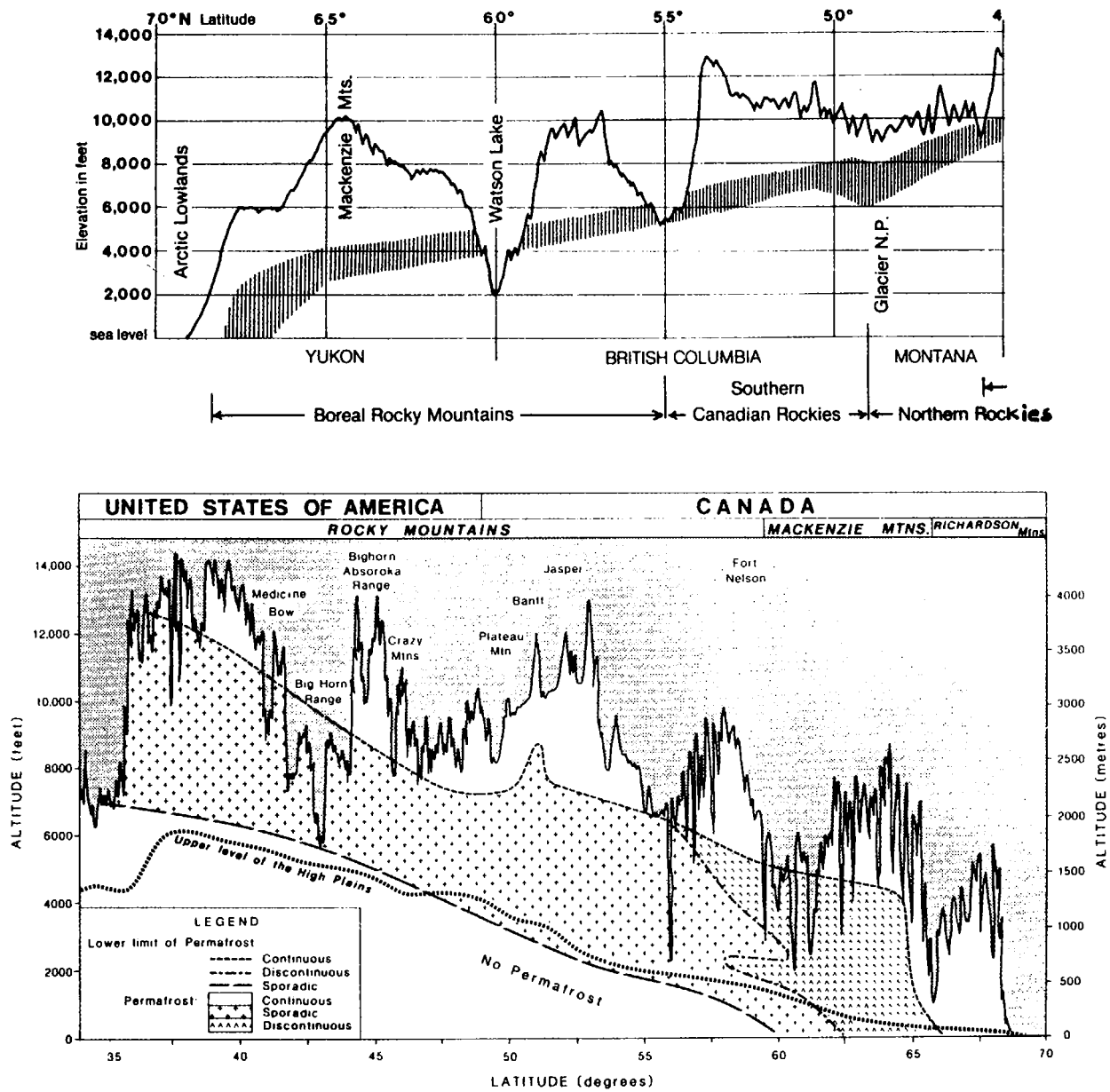


FIGURE 5. Upper: Timberline elevation along north-to-south section of the Rocky Mountains (Arno and Hammerly, 1984). Lower: Permafrost zone variations along south-to-north section of the Rocky Mountains (Harris, 1988).

### 3. CLIMATE AND EROSION PROCESSES IN MOUNTAINS

Climate provides the radiant energy and moisture inputs into erosional systems. These energy and moisture inputs encounter resistances and buffers which delay the initiation of erosion processes substantially and highly variably over space. The local available relief is important, as are the thermal diffusivity and hydraulic conductivity of the regolith, in controlling the depth of penetration of a temperature wave and a slug of moisture in a single event. Storage by snow and lakes can delay the climate effect over seasonal time scales. Glaciers, aquifers, soils, and vegetation may introduce time lags of decades to millennia. As recently demonstrated for British Columbia (Slaymaker, 1987; Church and Slaymaker, 1989), the climatic pertur-

bation of the Wisconsin Glacial event is still exercising a dominant effect on clastic sediment and solute transfers in that mountain region. It is claimed by Church and Slaymaker (1989) that all recorded responses in British Columbia's sediment systems are transient.

#### *Vegetation and Treeline Response*

It is generally understood that ecological adjustments to climate changes are intermediate between those of glacial mass balances and erosion (Roberts, 1989). This implies that glaciers will reflect climate change most rapidly, that timberline will respond more slowly, and that erosional systems will respond most conservatively. In studies of mountain zonation, there is commonly confusion in the inter-

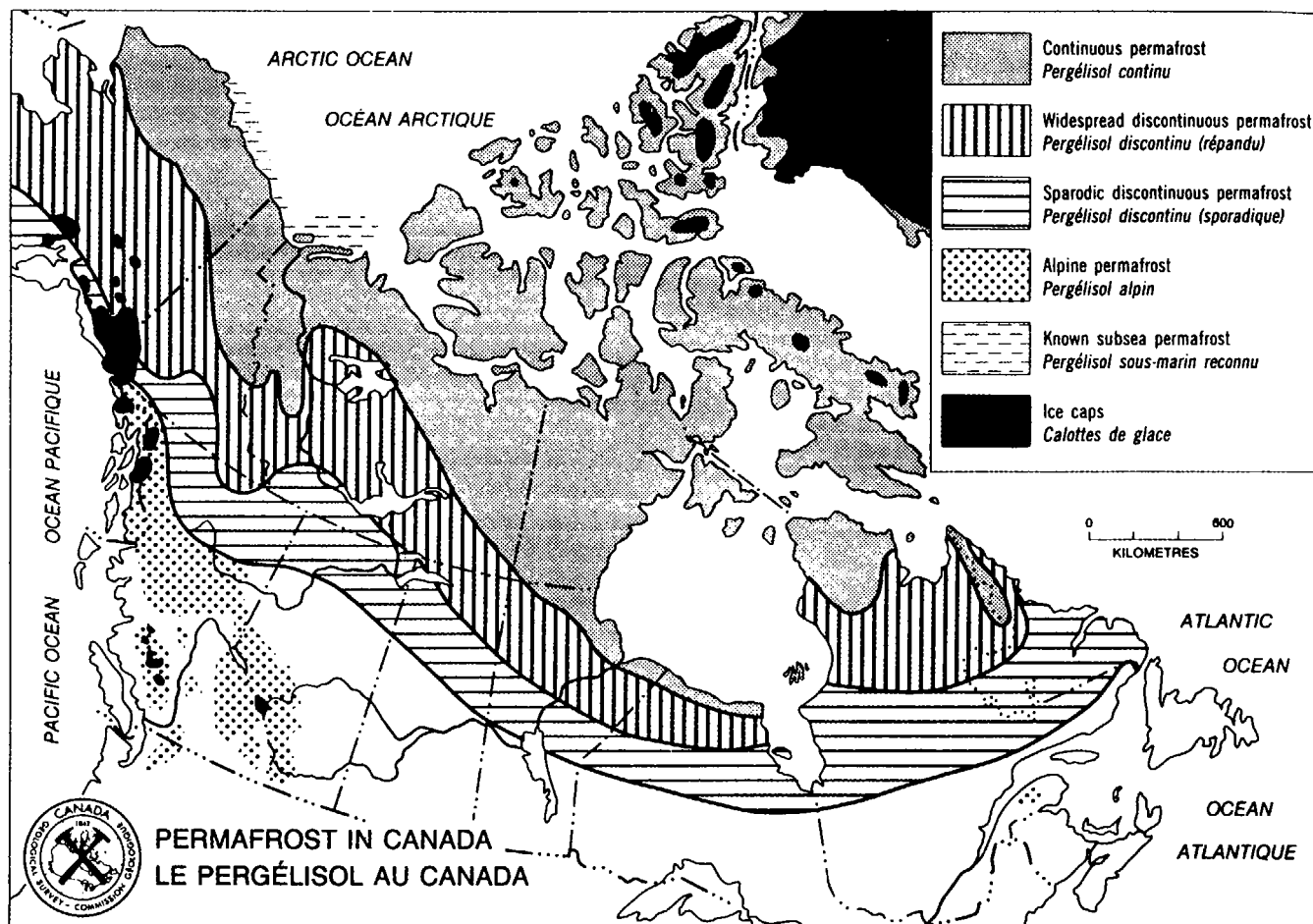


FIGURE 6. Permafrost in Canada.

pretation of timberline, the lower limit of permafrost, and the lower limit of periglacial erosion because all three zones are migrating in a vertical sense at different rates in response to climate change. It is unusual to find a clarification as to whether the investigation is describing an equilibrium response or a transient response. The work of Payette *et al.* (1989) is a brilliant exception to this generalization.

"The transition from forest to tundra on a mountain slope is one of the most dramatic ecotones on earth. . . . For some reason, or combination of reasons, trees grow only up to a certain elevation" (Price, 1981:271). Timberline is the term used for the entire transition from closed forest to open treeless tundra (MacDonald, 1987). The mean isotherm of 10°C in the warmest month corresponds fairly closely with timberline, though snow, wind, sunshine, and a variety of biotic factors cause local variations. In the Canadian Cordillera, vegetation zonation toward timberline varies according to location. In the perhumid "hypermaritime" locations of the west and south coast of British Columbia, a Mountain hemlock zone (mountain hemlock, amabilis fir, and yellow cedar) lies below timberline; in the more continental locations of the southern and central interior, an Engelmann spruce-subalpine fir zone lies adjacent

to timberline, and in the north a spruce-willow-birch zone adjoins alpine tundra.

In general, timberline declines by an average of 100 m per degree of latitude such that at Haines Junction, Alaska, at 60° North and 10° latitude north of Garibaldi, the timberline is at approximately 900 m, and at 69° North in the northern Yukon, timberline and the northern forest border merge (Figure 5). If it is the summer warmth (specifically 10°C in the warmest month) that controls timberline, in a latitudinal sense we still do not know the mechanism whereby low temperatures stop tree growth (Price, 1981).

It appears that one equilibrium response of timberline to a 1°C change in mean temperature is a 150–200 m change in elevation (Davis, 1988; Roberts, 1989). Unfortunately, we do not know how long it takes for the equilibrium response to be achieved. Nor do we have a clear idea of the way in which precipitation changes influence the extent of the timberline dislocation. Payette *et al.* (1989) note the importance of autogenic control in timberline ecosystem resilience and show for the Quebec treeline that there is as yet no conclusive evidence of a positive vegetation response to global warming.

In that the goal of this paper is to examine the relation-

SEDIMENT TRANSFER  
MECHANISMS

## LANDFORMS

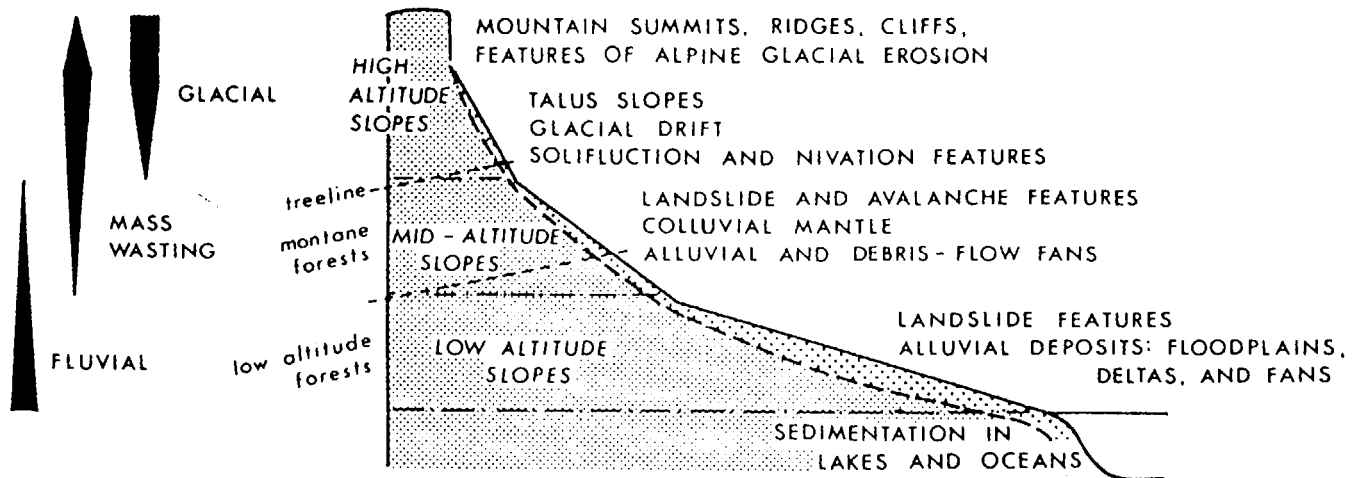


FIGURE 7. Zonation of major Holocene landforms and geomorphic processes (Muhs *et al.*, 1987).

ship between climate change and erosion and that two of the most important parameters controlling erosion processes in Canada's Cordillera are presence or absence of vegetation and the phenology of permafrost, any attempt to establish a direct causal explanation must be provisional.

*Permafrost and Periglacial Activity and Mountain Zonation*

There are two ways of considering mountain zonation: (a) vertical zonation resulting from changing altitude (e.g., Troll, 1972; Caine, 1984) and (b) horizontal zonation, caused by latitude, continentality, "mountain mass" effect, aspect, and pathways of gravity-driven processes of denudation. Whichever way it is approached, mountain zonation provides a framework for integration of the morphological and dynamic aspects of mountain environments (Hollerman, 1973, 1980; Ives and Barry, 1974; Slaymaker and McPherson, 1977; Price, 1981).

Not only is there a vegetation zonation but there is a zonation of geomorphic processes associated with contrasts above and below the lower limit of permafrost and the lower limit of periglacial activity (Luttmerding and Shields, 1976).

Permafrost in the Cordillera is a continuous zone at higher elevation and higher latitudes (Figure 6). Below the continuous zone there is a discontinuous zone down to the lower altitudinal limit of permafrost. In Yukon Territory (Burgess *et al.*, 1982; Burn, 1982), permafrost occurs in valley bottoms; in southern British Columbia, the distribution of mountain ("sporadic") permafrost is influenced by relief, vegetation, hydrology, snow cover, fire, glacier ice, and soil and rock type. Periglacial activity is sometimes thought to be coextensive with permafrost (e.g., Harris, 1988). Harris (1981) has shown a rather close association between the lower limit of permafrost and lower limit of periglacial activity in alpine areas in the Canadian Rockies. As far as the continental climate mountains of the Eastern Cordillera are concerned this approach may be useful; for

the maritime climate mountains of the Western Cordillera such an approach is confusing, primarily because the effect of high snowfalls is to insulate the ground and inhibit permafrost development even in elevation zones where air freeze-thaw frequency is high and periglacial activity has been monitored (Mackay and Mathews, 1974). As a result, in Garibaldi Park at 50° North, the lower limit of permafrost is at 2,300 m, timberline is at 1,850 m, and the lower limit of periglacial activity is at 1,650 m. Snow accumulation early in the fall, before ground freezing, seems to be the most important factor. Permafrost is comparatively rare; timberline is comparatively low, as is the lower limit of periglacial activity associated with unvegetated zones immediately adjacent to glacier snouts.

A conceptual model of the implication of this vertical zonation demonstrates the huge contrasts between low altitude, mid-altitude, and high altitude slopes in this region. High altitude in the coastal mountains is above timberline; mid-altitude is from timberline to base of subalpine mountain hemlock zone; and low altitude corresponds to the coastal western hemlock zone (Figure 7).

Harris (1988) defines the alpine periglacial region as low latitude permafrost area above 500 m. He points out that most of the zonal (polar) permafrost landforms occur in alpine areas with a relatively moist climate and high ground ice content but that in drier climates such landforms are commonly lacking except for special topographic locations. By contrast, in the perhumid coastal mountains permafrost landforms are commonly lacking because of insulating effects of snow.

Needle ice growth is of major importance in the maritime mountains (Mackay and Mathews, 1974), encouraging substantial downslope movement; in the continental mountains contraction cracking and frost comminution are more common. The landforms that are most characteristic and which are best developed in the moister areas of the

continental alpine areas are lobate rock glaciers, palsas, pingos, contraction cracks, patterned ground, hummocks, thufurs, and rock streams (French, 1976).

The lower limit of permafrost also declines northwards, but more rapidly than the timberline at about 140 m per degree of latitude (Brown and Péwé, 1973). In the Haines Junction area the lower limit of permafrost is at about 900 m, almost coincident with local timberline.

While at Garibaldi the lowest visible indicators of permafrost are 450 m above timberline, in the Rocky Mountains of Alberta at 50° North timberline is at 2,300 m and sporadic permafrost is recorded 1,000 m below timberline (Harris, 1988). Thus timberlines are lower in maritime mountains and higher in continental mountains; the reverse is true for the lower limit of permafrost. Associated with the higher timberline is the higher glaciation level and equilibrium line altitude associated with continentality. All these effects work together to generate an extensive zone of periglacial activity in the Rocky Mountains by comparison with the rather more limited periglacial zone in the Coast Mountains. On Vancouver Island and the Queen Charlotte Islands there is effectively no periglacial zone. Slaymaker and Zeman (1975) have described the effects of continentality on watershed hydrology in the Coast Mountains.

Evidently, the search for direct links between mean climate parameter changes and morphoclimatic adjustments is meaningless at the 50–100 year time scale. A different direction towards the resolution of this problem has been suggested by Ahnert (1987) and Eybergen and Imeson (1989). They propose a statistical approach to the relationship between "relevant meteorological events" covered by the instrumental record and "climate sensitive" processes. The changing trend in climate sensitive processes needs to be looked at via magnitude-frequency analysis of high intensity rainfalls, strong winds, and frost, and the time of year and the sequencing of extreme events is clearly important. This makes a promising link with the approach outlined in Table 4.

#### 4. PROBABLE GEOMORPHIC IMPACTS ON CANADA'S WESTERN MOUNTAINS

For all the reasons advanced in sections 1–3 of this paper, it seems wise to characterize the relationship between erosion processes and climate in qualitative ways and to predict tendencies rather than actual rates of activity of erosional processes.

##### *Insular Mountains*

Vancouver Island and the Queen Charlotte Ranges constitute a distinctive mountain region. Periglacial activity, permafrost, and glaciers are effectively non-existent, although islands of alpine tundra with precipitation greater than 4,000 mm occur. Snowfall at higher elevations yields high intensity floods during rain-on-snow events through the October to February period. These mountains are dominated by mass wasting and fluvial activity (Alley and Thompson, 1978; Roberts and Church, 1986). It is hard to imagine that increases in precipitation and temperature of the order of magnitude contemplated during the next

sixty years will have any noticeable effect on geomorphic process. Debris torrent activity could be accelerated if the frequency of intense rainstorms is significantly increased (Slaymaker, 1988).

##### *St. Elias and Coastal Mountains*

To the extent that heavy snow in winter (> 25 m) insulates the surface, permafrost is sporadic and only at the highest elevations. Glacier ice is widespread; surging glaciers are a common feature in the northern part of this region. Wetter and warmer conditions may intensify glacial dynamism. Chemical weathering is relatively active, associated with late-lying snow patches and large quantities of water circulating through jointed bedrock (Gallie and Slaymaker, 1985). Gelifluction is a function of short period frost in spring and fall plus the large amount of melt-water. Patterned ground is therefore small scale except on broad ridges where wind keeps snow to minimal accumulations. The permafrost zone is substantially above timberline on the western slopes (Barry, 1981; Johnson, 1986).

Substantial impact of summer warming can be anticipated, especially on the northeastern slopes where the permafrost presently extends to timberline, and on the heavily glacierized regions.

##### *Subarctic Dry Interior Mountains*

In these mountains permafrost is normally present close to timberline and is universal above timberline. Timberlines are substantially higher than those of the coastal mountains in equivalent latitudes. The comparison is complicated by the comparative recency of glacier recession from low-lying areas on the coastal side (e.g., at Dry Bay, where the Alsek River enters the Gulf of Alaska, timberline is at 300 m; 50 km inland the timberline is over 900 m).

Annual and diurnal thermal ranges are so great that in spite of the low moisture supply periglacial activity is marked. Also, because permafrost is omnipresent gelifluction is vigorous (Poser and Schunke, 1983). However, few of these mountain ranges appear to have been glaciated, presumably because of their continuing low moisture supply throughout the Quaternary. This is the region of cryoplanation and open system pingos (Hughes, 1969).

It is in this region that the greatest impacts of climatic change can be anticipated. Massive thermokarst development could dislocate airport runways, road construction, pipeline stability, and construction projects generally.

##### *Temperate Interior Alpine Mountains*

Timberline is higher here than in both coastal mountains and subarctic mountains; the lower limit of periglacial activity is lower than in the coastal mountains but higher than in the subarctic mountains. It is a transition zone both in a west-to-east and in a south-to-north direction (Alley and Young, 1978). Heavy snowfall maintains glaciers and local ice caps in the Columbia Mountains.

Climatic change scenarios for this region suggest the possibility of glacier expansion due to wetter and warmer conditions; increased snow accumulation and avalanche hazard has reduced periglacial activity because of increased snow depths and ambient temperatures.

### Temperate Dry Interior Mountains

The work of Harris (1988) provides helpful descriptions of the nature of periglacial activity in these mountains. Sporadic permafrost occurs over a wide elevation range; this is followed by a narrow zone of discontinuous permafrost, and finally the continuous permafrost zone above 2,000 m or so. Harris emphasizes the variability of perma-

frost resulting particularly from cold-air drainage and snow phenology. Recent work by Smith (1987a, 1987b) has provided a valuable description of frost heave and gelifluction in this region.

Climatic change scenarios for this region suggest a considerable reduction in periglacial, freeze-thaw activity and loss of sporadic permafrost over a wide elevation range.

## CONCLUSION

We do not know what the precise effects of climate change on erosion processes in the mountain regions of western Canada will be. Equilibrium responses of timberline, permafrost limits, and lower limit of periglacial erosion may or may not occur within the appropriate time frame of sixty years so as to allow prediction of erosional effects of climate change in Canada's mountains. Improved understanding of climate erosion systems in mountains is urgently required. The use of paleoclimatic analogues should be pursued with care as it is not clear that such analogues are realistic for the mid-twenty-first century. Scenarios based on physical and statistical arguments and which rely on good understanding of present climate conditions can be developed to estimate consequences of

changes in atmospheric circulation and dominant air-mass conditions. The use of proxy data from tree-ring analysis, lake sediment cores, and glacier cores seems most promising. It is also clear that considerable developments are ahead in linking global climate models with more detailed hydrologic models (Klemes, 1985). It seems probable that a fuller understanding of regional mountain water balances and the nature of transient vegetation, permafrost, and sediment and solute flux responses to climate change in mountains are the central research needs of the next decade. Only with improved understanding of such mountain processes can principles of sustainable development be applied.

## REFERENCES

- Ahnert, F., 1987: An approach to the identification of morphoclimates. In Gardiner, V. (ed.), *International Geomorphology 1986*, Part 2: 159-188.
- Alley, N. F. and Thompson, B., 1978: Aspects of environmental geology, Queen Charlotte Islands. B.C. Ministry of the Environment Resource Analysis Branch Bulletin 2. 65 pp.
- Alley, N. F. and Young, G. K., 1978: Environmental significance of geomorphic processes in the northern Skeena Mountains. B.C. Ministry of the Environment Resource Analysis Branch Bulletin 3. 83 pp.
- Alley, W. M., 1984: On the treatment of ET, soil moisture accounting and aquifer recharge in monthly water balance models. *Water Resources Research*, 20: 1137-1149.
- Arno, S. F. and Hammerly, R. P., 1984: *Timberline*. The Mountaineers, Seattle, Washington. 304 pp.
- Barrett, G. E., 1979: Changes in the discharge of selected rivers in British Columbia. Unpublished Honours thesis, University of British Columbia, Vancouver, B.C.
- Barry, R. G., 1981: *Mountain Weather and Climate*. Methuen, London. 313 pp.
- Brown, R. J. E. and Péwé, T. L., 1973: Distribution of permafrost in North America. *Proceedings of the Second International Conference on Permafrost*, pp. 71-100.
- Burgess, M. M. et al., 1982: Yukon ground temperature data: 1966 to 1981. *Earth Physics Branch Open File 82-1*. Energy, Mines and Resources, Ottawa. 138 pp.
- Burn, C. R., 1982: Yukon temperature cycles. *The Albertan Geographer*, 18: 11-27.
- Caine, N., 1984: Elevational contrasts in contemporary geomorphic activity in the Colorado Front Range. *Studia Geomorphologica Carpatho-Balcanica*, p. 18.
- Chilton, R. R. H., 1981: *A Summary of Climatic Regimes of B.C.* Assessment and Planning Division, B.C. Ministry of Environment. 46 pp.
- Church, M., 1988: Floods in cold climates. In Baker, V. R. et al. (eds.), *Flood Geomorphology*, pp. 205-229.
- Church, M. and Slaymaker, O., 1989: Disequilibrium of Holocene sediment yield in glaciated B.C. *Nature*, 337: 452-454.
- Clark, R. A., 1987: Hydrologic design criteria and climate variability. In Solomon, S. I. et al. (eds.), *IAHS Publication 168*. 640 pp.
- Davis, M. B., 1988: Ecological systems and dynamics. In: *Towards an Understanding of Global Change*. National Academy Press, Washington, D.C., pp. 69-106.
- Eybergen, F. A. and Imeson, A. C., 1989: Geomorphological processes and climatic change. *Catena*, 16: 307-319.
- Ferguson, H. M., 1988: *The Changing Atmosphere: Implications for Global Security*. Toronto, June 27-30, 1988.
- French, H. A., 1976: *The Periglacial Environment*. Longman, London. 309 pp.
- Gallie, T. M. and Slaymaker, O., 1985: Hydrologic controls in alpine stream chemistry. *Proceedings of the 14th N.R.C. Hydrology Symposium*, 287-306.
- Gleick, P. H., 1986: Methods for evaluating the regional hydrologic impacts of global climate change. *Journal of Hydrology*, 88: 97-116.
- Harris, S. A., 1981: Distribution of active glaciers and rock glaciers. *Canadian Journal of Earth Sciences*, 18: 376-381.
- , 1988: The alpine periglacial zone. In Clark, M. J. (ed.), *Advances in Periglacial Geomorphology*, pp. 369-413.
- Hollerman, P., 1973: Some reflections on the nature of high mountains. *Arctic and Alpine Research*, 5: A149-A160.
- , 1980: Naturraumliche Hohengrenzen und die Hochgebirgsstufe. In Jentsch, C. and Liedtke, H. (eds.), *Hohengrenzen in Hochgebirge*, pp. 75-117.
- Hughes, O. L., 1969: Distribution of open system pingos in central Yukon. *Geological Survey of Canada Paper*, 69-34. 8 pp.
- Ives, J. D. and Barry, R. G. (eds.), 1974: *Arctic and Alpine Environments*. Methuen, London. 999 pp.
- Johnson, P. G., 1986: Holocene paleohydrology of the St. Elias

- Mountains. *Geographie Physique et Quaternaire*, 40: 47-53.
- Klemes, V., 1985: Sensitivity of water resource systems to climate variations. *W.C.P. Rept. 98*, W.M.O. 143 pp.
- , 1988: A hydrological perspective. *Journal of Hydrology*, 100: 3-28.
- Kuhn, M., 1985: Reactions of mid latitude glacier mass balance to predicted climatic changes. In: *Glaciers, Ice Sheets and Sea Level*, N.T.I.S., Dept. of Commerce, Springfield, pp. 248-254.
- Luttmerding, H. A. and Shields, J. A., 1976: *Proceedings of a Workshop on Alpine and Subalpine Environments*. April 28-30, 1976, Victoria, British Columbia.
- McBean, G. et al., 1989: Climate change and its effects on British Columbia's waters and fish. Research Contract Report to Federal Department of Environment, N.H.R.I., Saskatoon.
- MacDonald, G. M., 1987: Postglacial development of the sub-alpine boreal transition forest of western Canada. *Journal of Ecology*, 75: 303-320.
- Mackay, J. R. and Mathews, W. H., 1974: Movement of sorted stripes, Cinder Cone. *Arctic and Alpine Research*, 6: 347-359.
- Meier, M. F., 1983: Snow and ice in a changing hydrological world. *Journal of Hydrological Science*, 28: 3-22.
- Muhs, D. R. et al., 1987: Pacific Coast and Mountain System. In Graf, W. L. (ed.), *Geomorphic Systems of North America*, pp. 517-581.
- Paterson, W. B., 1981: *The Physics of Glaciers*. Pergamon, New York. 380 pp.
- Payette, S. et al., 1989: Reconstruction of treeline vegetation response to climate change. *Nature*, 341: 429-432.
- Poser, H. and Schunke, E. (eds.), 1983: *Mesoformen des Reliefs im Leutigen Periglazial-raum Bericht*.
- Price, L. W., 1981: *Mountains and Man*. University of California Press, Berkeley. 443 pp.
- Roberts, L., 1989: How fast can trees migrate. *Science*, 243: 735-737.
- Roberts, R. G. and Church, M., 1986: The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges. *Canadian Journal of Forest Research*, 16: 1092-1106.
- Slaymaker, O., 1987: Sediment and solute yields in B.C. and Yukon. In Gardiner, V. (ed.), *International Geomorphology, 1986*, pp. 925-945.
- , 1988: The distinctive attributes of debris torrents. *Journal of Hydrological Science*, 33: 567-573.
- Slaymaker, O. and McPherson, H. J., 1977: An overview of geomorphic processes in the Canadian Cordillera. *Zeitschrift für Geomorphologie*, 21: 169-186.
- Slaymaker, O. and Zeman, L. J., 1975: Influences of altitude and continentality on watershed hydrology in the Coast Mountains. *Proceedings of the 10th N. R. C. Hydrology Symposium*, pp. 225-232.
- Smith, D. J., 1987a: Frost heave activity in the Mt. Rae area. *Arctic and Alpine Research*, 19: 155-166.
- , 1987b: Solifluction in the southern Canadian Rockies. *Canadian Geographer*, 31: 309-318.
- Solomon, S. I., Bevan, M., and Hogg, W. (eds.), 1987: The influence of climate change and climatic variability on the hydrologic regime and water resources. *IAHS Pub. 168*. 640 pp.
- Thorntwaite, C. W. and Mather, J. R., 1955: The water balance. *Publications in Climatology*, 8: 1-104.
- Troll, C., 1972: Geocology and the world-wide differentiation of high mountain ecosystems. In: *Geocology of the High Mountain Regions of Eurasia*, pp. 1-16.