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The Effect of Climate Change on Floods in British Columbia

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A hydrological modelling of the flood response of two watersheds to climate change are presented. The two study watersheds are the Upper Campbell and the Illecillewaet watersheds located in British Columbia. The first watershed is a maritime watershed located on the east slopes of the Vancouver Island mountains whereas the second watershed is located in the Selkirk Mountains in Eastern British Columbia. The Canadian Climate Centre General Circulation Model (CCC GCM) has been used for the estimation of the effect of the climate change on meteorological parameters. The CCC GCM is a steady state model and the output of the 1991 run has been used. In addition to the changes in the amounts of precipitation and temperature usually assumed in hydrological climate change studies, other meteorological and climatic parameters are also considered; specifically, the effect of climate on the spatial distribution of precipitation with elevation, and also on cloud cover, glaciers, vegetation distribution, vegetation biomass production, and plant physiology. The results showed that the mean annual temperature in the two watersheds could increase by more than 3°C and the annual basin-wide precipitation could increase by 7.5% in Upper Campbell watershed and by about 17% in the Illecillewaet watershed. As a result, the mean annual runoff will increase by 7.5% in the Upper Campbell watershed and 21% in the Illecillewaet basin. For the study of floods, nine flood parameters have been investigated, the total number of flood episodes, the flood days per year, the duration of flood events, the annual flood volume, the mean flood flow, the mean flood peak, the annual maximum flood peak, the day of occurrence of the centroid of flood volume, and the day of occurrence of annual maximum flood peak. These nine parameters were extracted from the hydrographs of the two study watersheds using the double long-term mean daily flow. The study showed that, under the climate change scenario, the floods in the maritime Upper Campbell watershed would increase, on average, in magnitude by 14%, in volume by 94%, in frequency by 11%, and duration by 44%. The timing of the floods would remain almost unchanged, and the centroid of flood volume would shift earlier by only 2 days. In contrast, in the interior mountain Illecillewaet watershed, the floods would decrease, on average, in magnitude by 7%, in volume by 38%, and frequency by 23%. The duration of flood events, under the altered climate scenario, would remain, essentially, unchanged increasing by only 2.6%. Also, the study showed that in the Illecillewaet watershed the largest change between the altered climate and the present climate scenarios would be the timing of floods since the centroid of flood volume would occur 20 days earlier. The above changes in the flood response of the two study watersheds can be explained by the changes in the distribution and form of annual precipitation. These results indicate that different management procedures will be needed to minimize the effects of climate change on the flooding of the two climatically different watersheds and the regions that they represent.

Introduction

This study sets out to investigate the possible effects of climate change on flood events of two mountainous watersheds located in different climate regions of British Columbia by considering most of the meteorological and vegetative factors that are likely to be affected by the climate scenario. This approach is an extension of previous referenced work which accounts mainly for changes in precipitation, temperature, and hydrologic regime of the two study watersheds. In this study the U.B.C. watershed model is used for the estimation of the flood response of the watersheds. The latest version of the U.B.C. model can account for changes in the vegetation cover and physiology, elevation, aspect, cloud cover and other meteorological factors.

It is common knowledge today that the global atmospheric concentration of carbon dioxide (CO_2) have been dramatically increased over the previous century (Keeling *et al.* 1982), and if the present rate of increase continues the concentration of carbon dioxide will double by the middle or end of next century (Ripley 1987).

Global circulation models (GCMs) have been used to study the effects of the doubling of the concentration of carbon dioxide and the other greenhouse gases on the Earth's climate (Hansen *et al.* 1983; Manabe and Weatherland 1987; Wilson and Mitchell 1987; Canadian Climate Centre 1991). GCMs simulate the Earth's atmospheric circulation and give predictions of the changes in temperature, in the amount and distribution of precipitation and other climatic parameters under a doubling of the carbon dioxide concentration scenario. Such a change in climate is expected to have important implications for the hydrologic balance and water resources.

Numerous studies have dealt with the hydrologic impacts of climate change and these studies can be divided into two categories: 1) statistical methods and 2) hydrological modelling of the climate change. The first category of methods relies on statistical techniques, mainly regression analyses, for evaluating the hydrologic characteristics of a particular region. The resulting empirical equation relate climatic parameters, such as temperature and precipitation, to streamflow or snowmelt, and are used to evaluate the effect of climate change on the climatic parameters, and then estimate the change on the hydrological variables (Revelle and Waggoner 1983; Duell 1994). These methods assume that the relationships between temperature, precipitation, and streamflow will remain unchanged under future climatic conditions.

In contrast, the second category uses deterministic or conceptual hydrological models that contain physically-based mathematical descriptions of hydrologic phenomena. The input variables to the hydrologic models can be either hypothetical climate scenarios (Cooley 1990; Nash and Gleick 1991; Panagoulia 1991; Ng and Marsalek 1992) or the output of GCMs (Lettenmaier and Gan 1990; Kite 1993; Epstein and Ramirez 1994). Although the hypothetical climate scenarios are easy to develop, they are not particularly realistic, and often lack internal consistency (Gleick 1989). The combination of GCMs output and hydrologic models is more realistic although there are inherent uncertainties about the details of regional climate changes. The major problem of the current generation of global climate models is the limitation of their spatial resolution and the resolution of the output. Usually the output of GCMs is given for a much larger scale than the scale of even a large watershed. Interpolation and dissaggregation schemes have been used to overcome the spatial resolution limitation of the GCMs (Epstein and Ramirez 1994).

In Canada, most studies of climate change on the hydrology of watersheds have concentrated on watersheds where snowmelt is the major proportion of the streamflow, mainly because there is a strong influence on the snowpack, its melting rate, and melting period. However, it is also important to analyze the effects of climate change on rain fed watersheds and to compare with snowmelt watersheds. Few studies (Kite 1993; Loukas and Quick 1996) have considered the effects of climate change on vegetation distribution and transpiration and not only changes in temperature and precipitation. Most studies assumed that the basin itself would remain unchanged and ignored changes in vegetation pattern and physiology as well as changes in meteorological parameters, except for precipitation and temperature, that may be invoked by climate change. For example, climate change will affect not only the precipitation and temperature but also the distribution of glaciers, soil processes such as drainage capacity and soil quality; land surface processes such as erosion; vegetation characteristics, type and coverage. Furthermore, some meteorological parameters may be affected by feedback mechanisms. For example, climate change would not only change the proportion of rain and snow and the precipitation amount but would also affect the spatial distribution of precipitation and the cloud cover.

In addition to the above mentioned studies, it is important to estimate the effect of climate change on flood events since the timing and magnitude of floods are needed for the design and management of hydrotechnical projects.

The objective of this study is twofold. First, to incorporate the most important meteorological and geophysical parameters that are likely to change under a doubling of carbon dioxide scenario and influence the runoff; and second, to use the U.B.C. watershed model to analyze the effect of climate change on floods in the two watersheds located in different climatic areas and to compare the results.

The presentation of the study has been organized as follows. Firstly, a brief description of the U.B.C. watershed model is presented which is followed by the presentation of the study watersheds and the weather inputs used in the simulation. The effects of climate change on the various parameters studied in this research are then described and the application of the simulation procedure to the two study watersheds precedes the results and conclusions.

Hydrological Model

The U.B.C. watershed model will be used for the simulation of the effect of the changes of these parameters on the runoff of two watersheds. The U.B.C. watershed model was first developed 25 years ago, and has been updated continuously to its present form. This model has been applied to a variety climatic regions, ranging from coastal to inland mountain regions of British Columbia including the Rocky mountains, and the subarctic region of Canada. The model has also been applied to the Himalayas and Karakoram ranges in India and Pakistan, the Southern Alps in New Zealand and the Snowy mountains in Australia. This ensures that the model is capable of simulating runoff under a large variety of conditions.

The model conceptualizes the watersheds as a number of elevation bands. Each elevation band can have variable characteristics and land uses such as forested, open, impermeable, and glacierized areas. Precipitation and temperature data are used as input to the model. The model is used to distribute these meteorological data with the elevation. Based on temperature, the model estimates whether precipitation is rain or snow and estimates snowpack accumulation as a function of elevation. The runoff from rainfall, snowmelt and glacier melt is distributed into four runoff components, is achieved with a soil moisture control mechanism. The four runoff components, the fast or surface runoff, the medium or interflow runoff, the slow or upper zone groundwater runoff and the very slow or deep zone groundwater runoff are simulated by using the linear storage technique. Using this technique, the runoff from each land use portion of each band is calculated separately and it is added to the runoff from the other land use areas of the elevation band to produce the runoff from the band. This procedure is repeated for each elevation band and the summation of the runoff from all bands gives the watershed runoff for the time step which can vary from one hour to one day. Details of the model structure are given in Quick (1995).

For the present study the results of the 1991 run of CCC GCM have been used to estimate the changes in precipitation, temperature, and cloud cover. The changes in tree cover, density and physiology as well as the changes in the areal extention of glacierized areas have been estimated using contemporaty methods proposed in the international literature. The key features of the model are, its capability to incorporate changes in:

1) Tree cover and density.
2) Cloud cover and to calculate the resulting change in radiation energy exchange.

and to compute:

3) Changes in the form of precipitation from snow to rain and the corresponding changes in precipitation gradients with altitude in the watersheds.
4) Changes in snowmelt between forested and open areas, including the effects of north and south aspect, calculation of modifications in albedo and cloud cover and the consequent shortwave energy changes. The energy budget routine is especially important for this type of study and has been well proven on other studies.
5) Changes in glacial melt, which again depends on the energy budget method and is particularly sensitive to earlier melting of the seasonal snowcover on the glacier. This increased glacial melt is a clear indication of glacial retreat, especially when coupled to the lower snowpack accumulations.
6) Changes in evapotranspiration are estimated according to tree cover and temperature, but modified by the enhanced CO_2 effect on stomata.

Study Areas

The U.B.C. watershed model has been applied to two British Columbia watersheds, the Upper Campbell and the Illecillewaet watersheds. The first watershed, the Upper Campbell watershed, is located on the east side of the Vancouver Island mountains and drains to the north and east into the Straight of Georgia (Fig. 1). The 1,194 km^2 basin is very rugged with peaks rising to 2,200 m and the mean basin elevation is 950 m. At the lower elevations of the watershed a reservoir has been formed by a dam which controls Upper Campbell and Buttle lakes and is about 50 km long and up to 5 km wide.

The climate of the area is characterized as a maritime climate, with wet and mild winters and dry and warm summers. Most of the precipitation is generated by cyclonic frontal systems that develop over the North Pacific Ocean and travel eastwards. The annual precipitation is about 2000 mm, of which 60% is in the form of rain. The wettest period is the period between November to March whereas the precipitation during the six month period from April to September accounts for only 25% of the annual precipitation. Even though the rain is the major runoff producing mechanism in this basin, significant snowpacks are accumulated, especially at the upper elevations. However, the snowpack partly melts during the accumulation period from Oc-

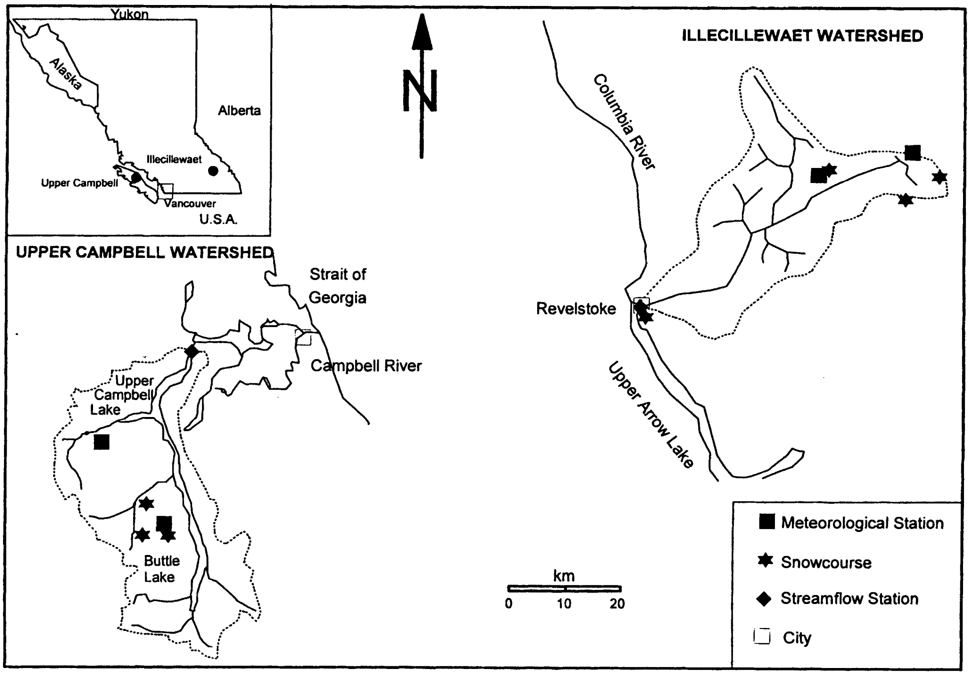

Fig. 1. Location of the Upper Campbell and Illecillewaet watersheds and the monitoring stations within the watersheds.

tober to April and strongly melts from May until the disappearance of snow at the higher elevations, usually by mid-August.

Although data from two meteorological stations were available in the watershed, one at 370 m and the other at 1,470 m, only daily precipitation and daily maximum and minimum temperature from the lower station have been used because the upper station was considered unreliable especially during intense snowstorms, probably from ice-capping of the gauge. Streamflow was measured at the mouth of the watershed. Additional data from three snowcourse sites, Lower Wolf Creek, Middle Wolf Creek, and Upper Wolf Creek at elevations 640 m, 1,070 m, and 1,490 m, respectively were used to compare the observed snowpack accumulation with the computed snowpack. Fig. 1 shows the locations of the streamflow gauge, the snow courses, and the hydrometeorological stations.

The second study watershed is the Illecillewaet River basin which is located on the west slopes of the Selkirk mountains in southeastern British Columbia. The area of the watershed is 1,150 km^2 and its elevation ranges from 1,000 m to 2,250 m. The Illecillewaet River is a tributary of the Columbia River and contributes to the Arrow Lakes reservoir (Fig. 1).

The climate of the area is continental, with cold winters and warm summers with frequent hot days. The basin is located about 500 km inland from the Coast Mountains and its climate is influenced primarily by the maritime Pacific Ocean air masses and by weather systems moving eastwards. The long-term average precipitation ranges from 950 mm at Revelstoke at an elevation of 443m which located close to the mouth of the watershed, to 2,160 mm at Glacier Mount Fidelity station at 1,875 m. The water equivalent of the average annual snowfall for the same stations is 445 mm and 1,518 mm, respectively. As a result, substantial snowpacks develop during the winter at all elevations in the basin. The snowpack in the valley bottom at Revelstoke is usually depleted by the end of April, but permanent snowfields and a glacier exist at the highest elevations. The rapid snowpack depletion in the lower and middle elevation ranges during the late spring is the dominant influence on the hydrology of the region.

In this study, data from three meteorological stations were used. Precipitation and temperature data were used from the Revelstoke station at 443 m, Glacier Rogers Pass station at 1,323 m, and Glacier Mount Fidelity station at 1,875 m. Also, the simulated snowpack accumulation was compared to observed data from three snowcourses. The snowcourses used are Glacier at 1,250 m, the Mount Fidelity at 1,875 m, and Mount Abbott at 1,980 m. Streamflow data from the station located at the mouth of the watershed were used to assess the calculated runoff from the watershed. Fig. 1 shows the location of these stations.

Weather Inputs

Simulated climatic data for $1xCO_2$ and $2xCO_2$ scenarios were obtained from the second-generation Canadian Climate Centre (CCC) GCM (Canadian Climate Centre 1991). This model is a 10-layer atmospheric model and has a resolution equivalent to 3.75°×3.75°, and unlike its predecessor and many of the other first-generation GCMs, has full diurnal and annual cycles, uses a simple ocean and sea ice model, and includes cloud optical properties feedback which exhibits a strong effect on the energy balance of the Earth's surface (Arking 1991). For the double carbon dioxide atmospheric concentration scenario, the output from this model shows a globally averaged surface temperature increase of 3.5°C and a 4% increase in precipitation and evaporation. These values are in the middle of the range of the predictions of other GCMs (Mitchell 1983; Manabe *et al.* 1981; Washington and Meehl 1983; Hansen *et al.* 1983).

Mean monthly values of climatological variables were obtained from a 10-year control run ($1xCO_2$) and a 10-year experimental run ($2xCO_2$) at a number of grid points near to the study basins. Although the output of GCMs is considered to be a realistic representation of the response of the atmosphere to the increase of the concentration of the greenhouse gases, there are still many uncertainties in climatic simulations from GCMs. This is particularly true for mountainous regions such as

Table 1 – The effect of climate change on meteorological parameters from the outpout of CCC GCM for Upper Campbell and Illecillewaet watersheds.

Element	Watershed	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Tempe-rature (°C)	Upper Campbell	3.5	2.3	4.0	3.5	3.2	3.3	3.1	2.8	3.0	3.3	3.3	3.0	3.2
	Illecillewaet	4.7	5.1	4.8	3.8	4.5	3.9	3.1	2.9	3.0	2.9	2.3	4.6	3.8
Precipi-tation (%)	Upper Campbell	33.7	28.2	2.4	-2.6	-25.4	-35.4	-21.4	33.3	65.8	7.1	21.4	38.3	14.9
	Illecillewaet	29.6	14.3	4.2	14.7	20.8	-21.1	4.4	5.1	47.4	3.6	26.6	29.6	15.5
Cloud Cover (%)	Upper Campbell	5.5	5.5	1.4	0	-14.1	-16.7	8.7	13.0	10.7	-2.7	2.5	1.3	7.7
	Illecillewaet	2.9	4.2	-3.0	-1.5	1.5	0	10.6	0	8.2	-2.9	2.7	0	1.5
Eva-poration (%)	Upper Campbell	0	-4.4	20.0	22.2	13.3	4.8	0	4.5	4.2	4.3	21.4	22.2	9.1
	Illecillewaet	41.2	-14.3	0	32.4	43.2	7.2	0	2.8	0	2.6	-15.8	9.7	8.3
Speed (%)	Upper Campbell	0	2.2	-9.8	-5.4	-14.3	-28.3	-31.7	10	-4.3	-14.6	2.2	6.7	-6.1
	Illecillewaet	-1.5	-8.6	-14.9	-13.8	4.8	-13.6	-2.0	-12.0	-4.2	-8.6	2.1	6.5	-3.2
Al-bedo) (%	Upper Campbell	-7.7	-7.7	0	0	0	0	0	0	0	0	0	0	0
	Illecillewaet	-5.0	-13.6	-13.6	-10.0	0	0	0	0	0	0	0	-5.3	0
Snow (%)	Upper Campbell	-100	-100	-100	-100	0	0	0	0	0	0	0	0	-100
	Illecillewaet	-80.6	-83.6	-94.3	-99.8	-100	0	0	0	0	-4.0	-86.8	-91.5	-88.4

British Columbia where the GCM does not incorporate the detailed topographical features but uses an oversmoothed terrain. For this reason, spatial disaggregation techniques have been proposed (Epstein and Ramirez 1994) to accommodate the variation of topography. Also, it is recommended (Canadian Climate Centre 1991) that users of GCM output interpolate the data from more than one point. In this study, interpolation is achieved by using B-splines. Fourth order polynomials are used for both latitude and longitude for the interpolation to the middle of the watersheds. The monthly difference of precipitation and temperature between the control and the experiment runs were used to adjust the data series of the meteorological stations to represent the climate change scenario.

Table 1 summarizes the average monthly change in climatic data for the two study watersheds. For Upper Campbell River these data indicate that the GCM predicts a temperature increase for every month which shows small variation from month to month and has an annual average of 3.2°C (Table 1). Also, the mean annual precipitation increases by about 15%, and the largest increase is observed in September (65.8%) and the largest decrease in June (35.1%). Annual evaporation increases by 9.1% and the largest increases are observed in November and December and the spring months from April to May. The GCM predicts that the cloud cover would increase by an average of 7.7% under the climate change scenario. The largest increase in cloud cover is observed in August (13%) and the largest decrease is indicated to occur in June (16.7%). The output of the GCM for the two runs showed that the small snowpack disappears in the climate change scenario.

The results for the Illecillewaet watershed showed similar changes (Table 1). The annual average temperature increases by 3.8°C with almost uniform distribution throughout the year. The average annual precipitation increase is 15.5% with September exhibiting the largest increase (47.4%) and June being the month with the only decrease (21.1%). Evapotranspiration increases on an annual basis by 8.3% but the pattern within the year is not consistent. There is only a small change in the cloud cover which on average increases only by 1.5%. The GCM predicts that under the altered climate there would be a dramatical reduction of snowpack which will be depleted by April instead of July or August.

Effect of Climate Change on Meteorological and Geophysical Parameters

Precipitation Spatial Distribution

The above monthly changes of precipitation and temperature were applied to the daily data series of the meteorological stations used in the study. However, in addition to the changes in precipitation amount, global warming would also result in more rainfall and less snow which in turn affects the spatial distribution of precipitation and the runoff response. Storr and Ferguson (1972) analyzed data from three Alberta watersheds and concluded that snowfall had an elevational gradient 10 times larger than the gradient of rainfall. Similar results have been reached in another study in coastal British Columbia (Schaefer and Nikleva 1973). The U.B.C. model calculates the precipitation in any elevation band using the equation

$$P_{i,j,l+1} = P_{i,j,l}(1+\text{GRAD}P)^{\Delta\text{elev}/100} \quad (1)$$

where $P_{i,j,l}$ is the precipitation from meteorological station i for day j and elevation band l, GRADP is the percentage precipitation gradient, and Δelev is the elevation difference between the meteorological stations and the elevation band.

The U.B.C. model, then, adjusts the precipitation gradient according to the temperature

$$\text{GRAD}P' = \text{GRAD}P' - S(T) \quad (2)$$

where $S(T)$ is a parameter which is affected by the stability of the air mass. The $S(T)$ parameter can be shown (Quick 1993) to be related to the square of the ratio of the saturated and dry adiabatic lapse rates, L_S and L_D, respectively *i.e.* $(L_S/L_D)^2$. A plot of $(L_S/L_D)^2$ *versus* temperature reveals an almost linear variation between -30°C and +20°C. The gradient of this linear approximation is 0.01, so that $S(T)$ can be estimated as

$$S(T) = 0.01\, T_{mean} \tag{3}$$

where T_{mean} is the mean daily temperature.

Cloud Cover

Another meteorological parameter that changes under a doubling of CO_2 scenario is the cloud cover. Cloud cover controls the amount of incoming solar radiation as well as the amount of longwave that is transmitted from the clouds. Changes in these parameters affect the energy balance on the Earth's surface which influences the temperature, evapotranspiration, and snowmelt rates. Especially for the snowmelt rates, a recent study in British Columbia showed that an increase in cloud cover by 25% would cause the snowpack to melt about 15 to 20 days earlier (Assaf and Quick 1991).

The U.B.C. model calculates the cloud cover, C_L, as a function of the daily maximum and minimum temperature, T_{max} and T_{min} as,

$$C_L = 1 - \frac{T_{max} - T_{min}}{D_R} \tag{4}$$

where D_R is the daily temperature range for open sky conditions. The calculated cloud cover is, then, modified by the per cent monthly changes of cloud cover derived by the CCC GCM output.

Vegetation

It is known that vegetation exerts a major influence on the microclimate of a particular site, regulating the temperature, moisture, and wind regime which in turn will influence the quantity and quality of runoff. Changes in vegetation can cause decreased evapotranspiration, increased erosion and degradation in water quality. These changes in evapotranspiration can then affect the availability of water and hence the runoff from a particular site. Also, the vegetation coverage affects the interception losses and the antecedent soil moisture conditions.

Many recent studies have dealt with the effects of climate change on vegetation. Three possible effects of climate change on vegetation have been identified so far. The first effect would be the stomata closure (Morison 1987; Cure and Acock 1986; Parry 1992). The second effect would be the increase in the production of biomass (Post *et al.* 1992) which may offset the decrease of transpiration due to stomata closure. The third effect would be the areal and altitudinal redistribution of vegetation.

Table 2 – Description of land uses by elevation band of Upper Campbell watershed.

Band	1	2	3	4	5	6	7
Mean Elevation of Band (m)	223	406	721	983	1238	1485	1939
Area of Band (km^2)	66.7	218.4	218.4	218.4	218.4	218.4	34.8
				$1xCO_2$			
Forested Area (%)	0	91	92	91	71	49	26
Tree Canopy Density (%)	0	90	90	90	80	60	60
Impermeable Area (%)	100	9	8	9	29	50	73
				$2xCO_2$			
Forested Area (%)	0	96	100	100	96	92	92
Tree Canopy Density (%)	0	60	96	95	95	94	93
Impermeable Area (%)	100	4	0	0	3	7	8

Table 3 – Description of land uses by elevation band of Illecillewaet watershed.

Band	1	2	3	4	5	6	7	8
Mean Elevation of Band (m)	1,000	1,360	1,540	1,650	1,790	1,915	2,085	2,250
Area of Band (km^2)	230	115	115	115	115	115	115	230
				$1xCO_2$				
Forested Area (%)	91	92	92	94	93	51	50	44
Tree Canopy Density (%)	99	99	99	99	99	99	99	60
Impermeable Area (%)	9	8	8	6	7	39	40	41
Glacial Area (%)	0	0	0	0	0	0	0	33
				$2xCO_2$				
Forested Area (%)	0	0	95	96	96	95	95	70
Tree Canopy Density (%)	0	0	99	99	99	99	99	70
Impermeable Area (%)	10	10	5	4	4	5	5	10
Glacial Area (%)	0	0	0	0	0	0	0	22

Zoltai (1988) estimated that there would only be a small areal change in the Pacific Cordilleran ecoclimatic region which covers the western British Columbia, and the Cordilleran ecoclimatic province, which covers the Rocky Mountains and the northern interior of British Columbia. Hence, any change in these two regions should be restricted to altitudinal shift of vegetation.

Recent studies (Ozenda and Borel 1990; Fanta 1992) indicated that a 1°C rise in temperature would cause the altitudinal boundaries of tree line to shift upwards by 100-180 m in the European Alps and the Central European Mountains and the trees would occupy most of the present alpine zone (Korner 1992).

In this study the mean annual change in temperature for a doubling of CO_2 was used to calculate the upward shift of vegetation as described in the earlier studies above. Tables 2 and 3 list the percentages of land use in each elevation band for each climate scenario for the two watersheds. In the Upper Campbell watershed the first band is occupied by the Upper Campbell and Buttle lakes. The major changes in land use under the $2xCO_2$ scenario are that the second elevation band will be occupied by deciduous trees, like Arbutus and Garry Oak which now occupy the coastal fringe of the southeast Vancouver Island (Rowe 1972) and a reduction of the impermeable area because of the increase vegetation coverage (Table 2). In the Illecillewaet River watershed the major change is the expansion of the grass area at the expense of the forest at the two lower elevation bands and a reduction of the impermeable areas (Table 3). These changes in land use are in agreement with previous studies (Smith *et al.* 1992; Kite 1993).

The evapotranspiration from the vegetation has been reduced due to the closure of the stomata caused by the increase in carbon dioxide concentration by 30%. This value is in agreement with previous plant physiological studies (Cure and Acock 1986; Morison 1987; Parry 1992) and hydrological studies (Wigley and Jones 1985; Kite 1993). Also, the increased net ecosystem production was depicted in the increased tree covered area and the density of vegetation. However, these changes are highly qualitative since there is no direct way of expressing the effect of climate change on the biomass production more quantitatively.

Glaciers

Glaciers will also be strongly affected by these changes in precipitation, temperature and energy balance. Recent studies have shown that the glaciers are very sensitive to climate changes and are frequently used as indicators of past climate changes (Ripley 1987). Lauman and Reeh (1993) have studied the sensitivity of three glaciers in southern Norway to climate change and they concluded that one glacier located at low elevation will eventually disappear under a climate change whereas the others will lose significant mass. In another study in Greenland, Braithwaite and Olesen (1989) reported that a 3°C increase in mean annual temperature will increase glacier ablation by 150-170% whereas if the temperature increase is 5°C, the increase in glacier ablation will be 200-240%. The specific values of glacier ablation depend on the geographical area. Two studies in the vicinity of the two study watersheds (Pelto 1989; Moore 1992) reported that the glaciers in the area have decreased in size from the middle of this century to present.

A glacier which covers 76 km^2, exists at the higher elevation band in the Illecillewaet River watershed. By using a model proposed by Oerlemans and Wegener (1989), the area of the Illecillewaet glacier was estimated under a mean annual temperature change of 3.8°C. The results showed that the glacier area will reduce by one third of the present area, from 76 km^2 to 51 km^2 (Table 3).

Application-Results

In an earlier study, (Loukas and Quick 1996) hydrologic simulations indicate both similarities and differences in the overall responses of the two study watersheds. The increased biomass of vegetation due to climate change compensates the decrease of evapotranspiration due to changes in the physiology of the vegetation (stomata closure). In the Upper Campbell watershed, there is no change in the annual evapotranspiration whereas in Illecillewaet basin there is a decrease of 13% which is smaller than the values reported in other studies on similar watersheds in the area.

In the Upper Campbell watershed which is located in the Pacific coast of British Columbia, the change in the global climate results in increases of annual precipitation of 7.5% and temperature of 3.2°C whereas in the interior mountain basin of Illecillewaet the temperature increases by 3.8°C, and the annual precipitation increases by about 17%. The results of these changes are that the rain dominated runoff of Upper Campbell River basin is affected to a lesser degree (7.4% increase) than the snowmelt dominated runoff of Illecillewat River watershed which increases by 21%. This increase is mainly concentrated in winter months whereas there is a small decrease in the summer runoff.

In this study, the U.B.C. watershed model was calibrated using recorded streamflow for the Upper Campbell basin for the years 1983-1990, and for the Illecillewaet watershed for the years 1970-1990. Unfortunately, no additional data from Upper Campbell watershed were available. Table 4 shows the statistics for the calibration periods of the model for the two study watersheds. Runoff statistics indicate that the model simulates the recorded streamflow well. Also, snowpack measurements were compared with the computed snowpack accumulations. The years for which the model was calibrated were also used for the simulation of the climate change effect on the flood runoff from the two study watersheds.

In this study, the double long-term mean daily streamflow (Gellens 1991; Panagoulia and Dimou 1997) was used according to the positive "runs theory" (Dracup *et al.* 1980a, b) to determine the flood parameters. According to this screening procedure any flow above the threshold value is considered flood flow. The threshold values for the derivation of flood flows for the two study watersheds where calculated to be 143.2 m^3/s for the Upper Campbell watershed and 105.2 m^3/s for the Illecill-lewaet basin. Nine flood event parameters were analyzed: (1) the total number of

Table 4 – Calibration statistics of the U.B.C. model for the Upper Campbell and Illecillewaet watersheds.

Hydrological Year	Nash-Sutcliffe Efficiency (Eff.)	Coefficient of Determination (r^2)	Runoff Volume Diff. (dV, %)	Mean Observed Flow (m^3/s)	Mean Simulated Flow (m^3/s)
			Upper Campbell		
1983-1984	0.68	0.68	-0.4	75.5	75.2
1984-1985	0.77	0.80	-2.9	59.7	57.9
1985-1986	0.81	0.83	-6.2	75.5	70.8
1986-1987	0.73	0.73	0.8	89.6	90.3
1987-1988	0.62	0.64	0.3	70.2	71.8
1988-1989	0.64	0.64	4.4	63.6	66.4
1989-1990	0.80	0.81	4.9	65.5	68.7
1983-1990	0.74	0.74	0.3	71.6	71.6
			Illecillewaet		
1970-1971	0.91	0.92	-8.0	52.0	47.8
1971-1972	0.92	0.92	-1.6	63.1	62.1
1972-1973	0.90	0.90	6.0	43.0	45.5
1973-1974	0.91	0.93	-12.9	59.6	52.0
1974-1975	0.87	0.88	12.8	47.5	53.5
1975-1976	0.86	0.86	-7.8	65.5	60.4
1976-1977	0.88	0.89	11.5	44.7	49.8
1977-1978	0.87	0.88	-5.6	50.3	47.4
1978-1979	0.87	0.89	9.6	49.9	54.7
1979-1980	0.85	0.87	8.3	50.2	54.3
1980-1981	0.87	0.88	-12.5	55.5	48.6
1981-1982	0.86	0.87	0.3	57.0	57.1
1982-1983	0.79	0.80	6.7	52.3	55.8
1983-1984	0.84	0.84	-2.3	52.9	51.7
1984-1985	0.88	0.88	1.5	49.4	50.2
1985-1986	0.91	0.91	-6.8	54.3	50.6
1986-1987	0.82	0.85	13.3	51.9	58.6
1987-1988	0.88	0.90	11.6	49.4	55.1
1988-1989	0.74	0.85	22.6	47.3	58.0
1989-1990	0.90	0.91	-1.4	55.3	54.5
1970-1990	0.87	0.88	1.7	52.6	53.4

flood episodes, (2) the number of flood days per year, (3) the average duration of flood events, (4) the annual flood volume, (5) the average flood flow per year, (6) the mean flood peak, (7) the annual maximum flood peak, (8) the day of occurrence of the centroid of flood volume, (9) the day of occurrence of annual maximum flood peak. For the last two parameters, the counting of the days started the first day of the hydrological year, *i.e.* October 1st. The average results for the years of simulation will be presented separately for the two study basins.

Upper Campbell Watershed

Table 5 shows the simulation results for the flood parameters for the Upper Campbell watershed for the $1xCO_2$ and $2xCO_2$ scenarios. According to these results, the total number of episodes for the simulation period 1983-1990 would increase by five episodes (11.4%) under the $2xCO_2$ scenario. The flood days per year increase, on average, by about 14 days or 59%, under the climate change scenario. As a result, the average duration of the flood events would increase by about 2 days which represents a 44% increase over the duration of flood events in the present climate. Also, the simulations showed that the flood volume would almost double under the climate change scenario. The average annual flood volume would increase by about 17 cm or 94% over the $1xCO_2$ scenario.

Table 5 – Change of flood parameters for $1xCO_2$ and $2xCO_2$ scenario for Upper Campbell watershed.

Flood	Parameter	$1xCO_2$	$2xCO_2$	Change	Per cent Change
Episodes	Total Number	44	49	+5	+11.4
Flood Days	Average	24.14	38.43	+14.29	+59.2
	CV[1]	0.50	0.38		
Duration (days)	Average	3.83	5.53	+1.7	+44.4
	CV	0.21	0.19		
Flood Volume (cm)	Average	17.84	34.55	+16.7	+93.7
	CV	0.49	0.45		
Mean Flood Flow (m^3/s)	Average	257.33	267.87	+10.54	+4.1
	CV	0.25	0.10		
Mean Flood Peak (m^3/s)	Average	321.71	367.07	+45.36	+14.1
	CV	0.27	0.17		
Annual Maximum Flood	Average	528.29	613.53	+85.34	+16.1
Peak (m^3/s)	CV	0.26	0.19		
Day of occurrence of flood	Average	73.29	71.28	-2.01	-2.7
volume centroid	CV	0.70	0.46		
Day of occurrence of annual	Average	85.43	71	-14.43	-16.9
maximum Flood Peak	CV	0.94	0.58		

[1] CV is the coefficient of variation

Another significant effect of the climate change would be the increase of floods in magnitude. The mean flood flow would increase by 4%, the mean flood peak by 14%, and the annual maximum flood peak by 16%.

The altered climate scenario would not significantly change the distribution of the flood flow, as indicated by the results for the day of occurrence of the centroid of flood volume. The centroid of the flood volume is expected to occur, on average, two days earlier, under the climate change scenario. On the other hand, the annual maximum flood peak would occur, on average 14 days earlier in the hydrologic year.

The above results can be explained by examining the flood producing mechanisms in the Upper Campbell watershed. The main flood generating mechanism in the maritime watershed of Upper Campbell watershed is the rainfall. In the present climate the high flows are generated by high rainfall, occurring during late fall and winter months. In the altered climate scenario, the increase in mean annual precipitation is 7.5%, and the majority of this extra precipitation is in the form of rain which is expected to fall during the "wet" period from October to February (Table 6). At the same time, due to higher temperatures, there will be less snow especially at the middle elevations of the watershed. Since more rain is expected during the "wet" period of the year and because of the high response of rainfall runoff, higher flows are expected during this period (Fig. 2). Furthermore, the snowpack under the $2xCO_2$ scenario is expected to be highly transient and wet and thus contributing and sustaining the high flows even during the winter months. This extra snowmelt from the ripe snowpacks may result in prolonged flood events.

Table 6 – Average model results for $1xCO_2$ and $2xCO_2$ scenario for Upper Campbell watershed.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
							$1xCO_2$						
PET[1] (mm)	20	26	44	134	101	130	151	143	109	72	28	20	979
AET[2] (mm)	11	13	23	31	41	38	27	23	23	21	15	11	277
Rainfall (mm)	164	127	123	95	99	73	31	27	51	206	260	137	1,394
Snowfall (mm)	176	90	81	43	10	2	0	0	1	24	139	123	688
Snowpack[3] (mm)	370	470	512	461	294	106	29	5	6	21	145	238	
Runoff (mm)	170	146	139	142	201	244	137	73	54	123	210	167	1,804
							$2xCO_2$						
PET[1] (mm)	28	26	47	59	88	109	122	113	92	65	32	24	806
AET[2] (mm)	19	16	28	28	32	23	19	26	26	25	22	16	278
Rainfall (mm)	345	190	172	121	81	48	23	35	80	236	394	268	1,994
Snowfall (mm)	57	70	16	9	1	0	0	0	0	3	34	54	245
Snowpack[3] (mm)	3	23	48	62	99	65	38	23	11	3	0	1	
Runoff (mm)	305	241	202	158	116	90	57	40	53	120	279	274	1,937

[1] *PET* is the potential evapotranspiration;

[2] *AET* is the actual evapotranspiration and the soil storage;

[3] Snowpack is the snow water equivalent of the snowpack at the end of each month.

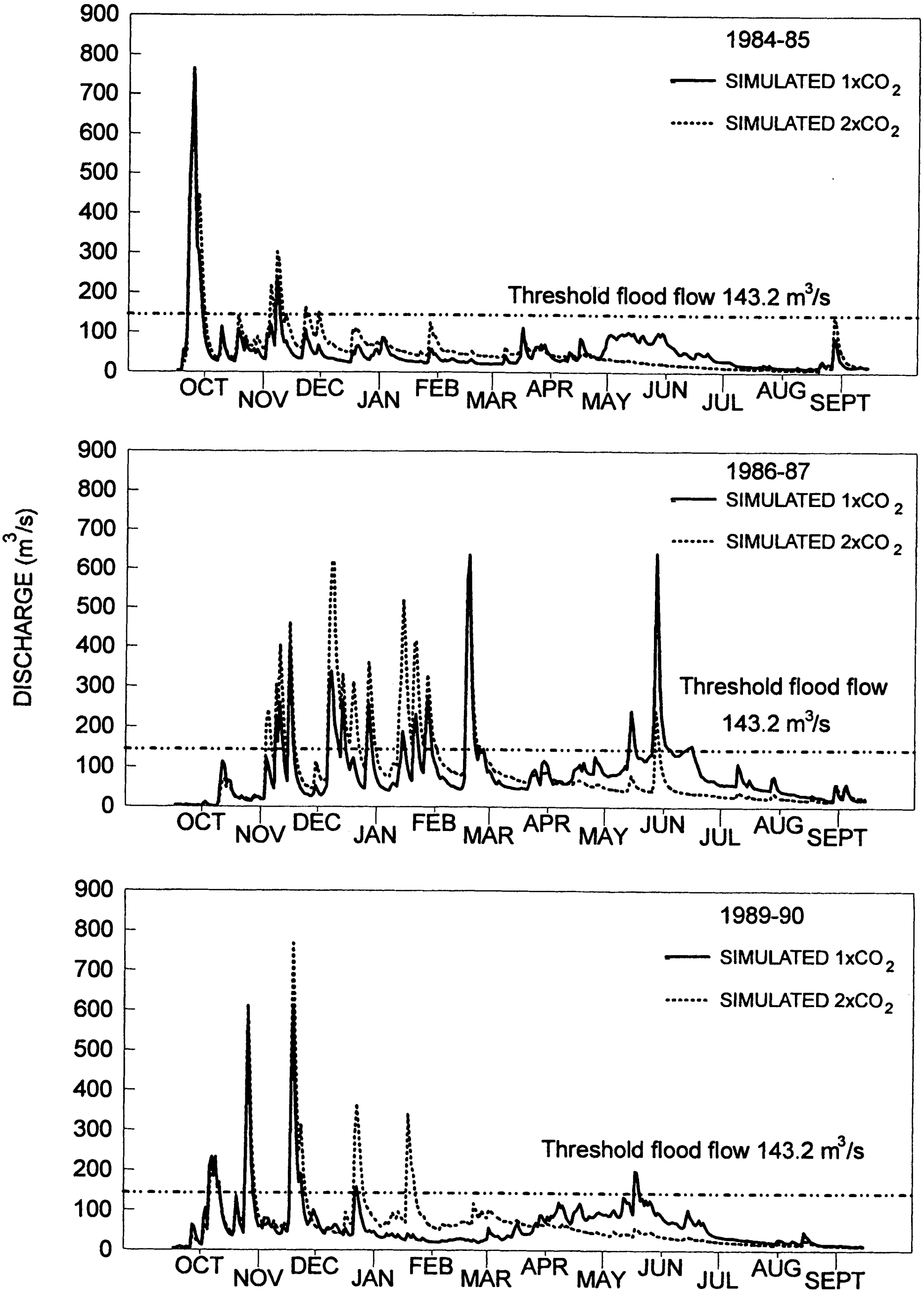

Fig. 2. Simulated hydrographs for Upper Campbell watershed for present and altered climate scenarios.

In Table 5, the coefficient of variation, *CV*, is shown for the flood parameters. It can be seen that for all parameters the variation from year to year is reduced under the $2xCO_2$ scenario. The concentration of flooding during the October to February period due to increased rainfall and the dramatic reduction of the snowpacks in the spring months may explain the reduction of variation from year to year, in the altered climate scenario.

Illecillewaet Watershed

Table 7 shows the simulation results for the Illecillewaet watershed. The simulations showed a decrease in the total number of flood episodes for the period 1970-1990. The number of flood episodes would be expected to reduce by 21 episodes or about 23%, under the climate change scenario. The number of flood days decreases by 19 days per year or about 28%, under the climate change scenario. On the other hand, the average flood duration slightly increases by 0.45 days or 2.6%, in the altered climate scenario.

More pronounced is the reduction of the average annual flood volume, under the $2xCO_2$ scenario, by 9 cm or about 38%. The mean flood flow and the mean flood peak are reduced by 5% and 7%, respectively. A larger reduction by about 11% in the magnitude of annual maximum flood peak has been shown. This change in the

Table 7 – Change of flood parameters for $1xCO_2$ and $2xCO_2$ scenario for Illecilleweat watershed.

Flood	Parameter	$1xCO_2$	$2xCO_2$	Change	Per cent Change
Episodes	Total Number	91	70	-21.0	-23.3
Flood Days	Average	69.45	50.35	-19.10	-27.5
	CV[1]	0.20	0.32		
Duration (days)	Average	17.22	17.67	+0.45	+2.6
	CV	0.49	0.65		
Flood Volume (cm)	Average	24.33	15.03	-9.30	-38.2
	CV	0.35	0.59		
Mean Flood Flow (m^3/s)	Average	151.20	143.27	-7.93	-5.2
	CV	0.07	0.09		
Mean Flood Peak (m^3/s)	Average	191.41	177.14	-13.27	-7.0
	CV	0.14	0.18		
Annual Maximum	Average	254.66	227.52	-27.14	-10.7
Flood Peak (m^3/s)	CV	0.21	0.21		
Day of occurrence of	Average	259	239	-20	-7.7
flood volume centroid	CV	0.038	0.1		
Day of occurrence of annual	Average	250	234	-16	-6.4
maximum Flood Peak	CV	0.06	0.31		

[1] CV is the coefficient of variation

magnitude of annual maximum flow between the two scenarios is significant and should be considered in the estimation of design flows for hydrotechic projects.

The hydrologic simulations showed that the largest change in the altered climate, would be observed in the timing of the flood flow. The centroid of the flood volume occurs 20 days earlier than under the present climate conditions. Similar result has been acquired for the timing of the annual maximum flood flow which would occur, on average, 16 days earlier.

The above results show that the Illecillewaet watershed has different flood response from the Upper Campbell watershed. The flow in the interior mountain Illecillewaet watershed is mainly generated by snowmelt and the high flows are observed during the late spring and summer months. In the altered climate scenario, the precipitation in the Illecillewaet watershed would increase by 17% (Table 8). The majority of this extra precipitation would be in the form of rainfall which is going to increase by about 87% per year. Most of this rainfall would fall at lower elevations. At higher elevations, even under the climate change scenario, the winter temperatures would still be low enough that the increased winter precipitation falls as snow which almost compensates for the decrease of snowfall during the spring and summer months. For these reasons, under the $2xCO_2$ scenario, the main flood producing mechanism would not be the snowmelt alone as is in the present climate conditions. The winter and spring rains along with the earlier snowmelt, due to higher air tem-

Table 8 – Average model results for $1xCO_2$ and $2xCO_2$ scenario for Illecillewaet watershed.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
							$1xCO_2$						
PET[1] (mm)	0	1	7	34	77	106	128	117	67	29	4	0	571
AET[2] (mm)	0	0	2	23	63	75	65	45	33	12	2	0	319
Rainfall (mm)	0	0	3	13	51	89	64	73	81	39	7	1	421
Snowfall (mm)	188	167	140	44	28	12	2	2	15	71	154	232	1,056
Snowpack[3] (mm)	627	795	833	905	642	250	38	12	64	66	205	437	
Glacier Runoff (mm)	0	0	0	0	0	5	50	93	35	8	0	0	191
Runoff (mm)	12	9	12	45	199	358	289	193	137	50	31	15	1,347
							$2xCO_2$						
PET[1](mm)	3	8	17	38	78	96	105	96	59	31	6	4	541
AET[2] (mm)	2	5	11	26	51	48	39	41	34	14	3	3	277
Rainfall (mm)	29	43	55	44	91	80	70	79	137	74	36	49	786
Snowfall (mm)	214	141	91	27	7	1	0	0	7	40	169	247	945
Snowpack[3] (mm)	603	685	678	489	131	4	0	1	120	27	182	408	
Glacier Runoff (mm)	0	0	0	0	6	29	61	71	29	7	0	0	203
Runoff (mm)	54	77	123	163	336	253	156	125	141	62	65	70	1,624

1 *PET* is the potential evapotranspiration;

2 AET is the actual evapotranspiration and the soil storage;

3 Snowpack is the snow water equivalent of the snowpack at the end of each month.

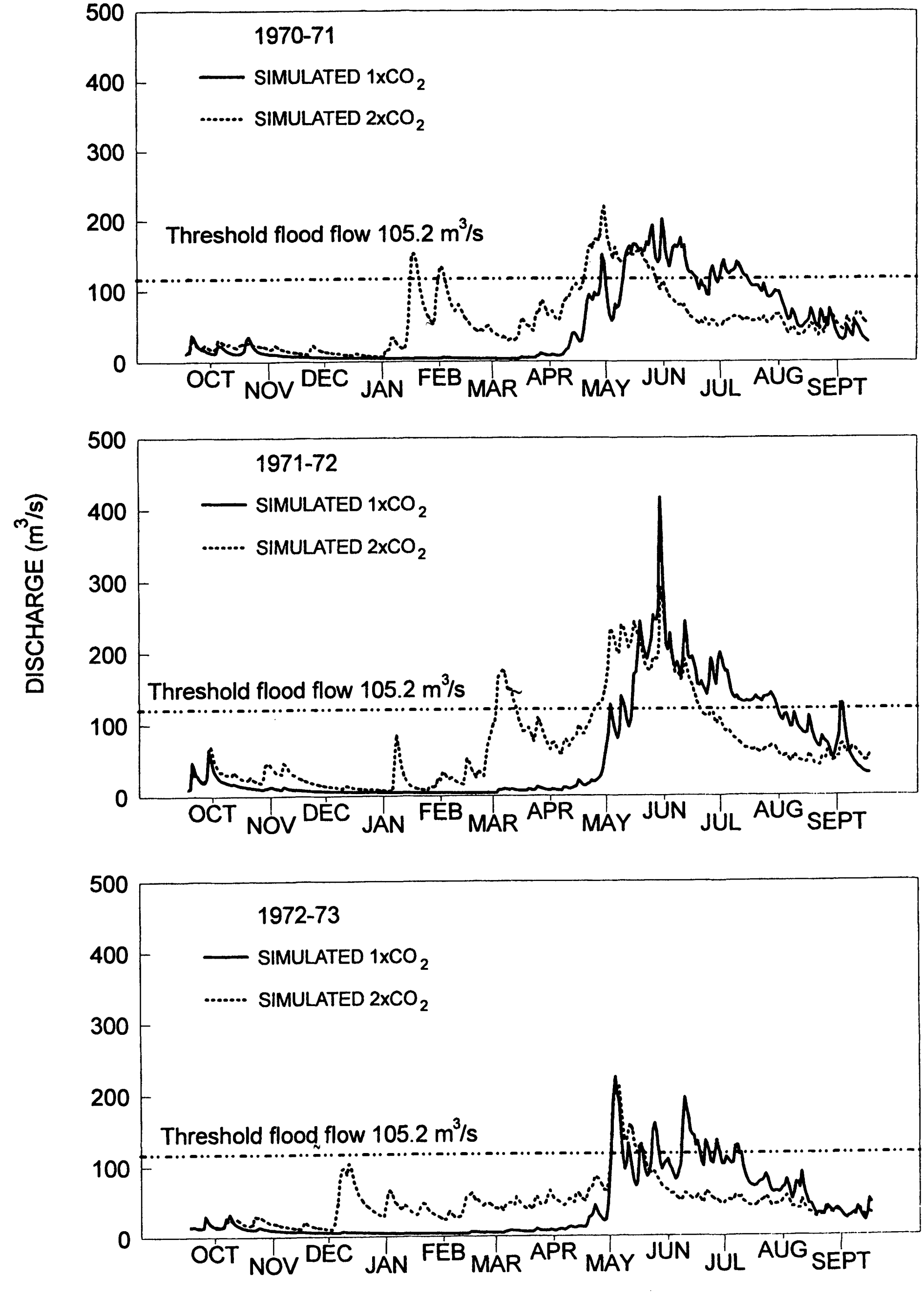

Fig. 3. Simulated hydrographs for Illecillewaet watershed for present and altered climate scenarios.

peratures, result in winter and spring high flows. On the other hand, the "wet" period is not any more concentrated in the late spring and summer months but it expands from January to August. As a result, the flow would be expected to be higher than at present conditions during the traditionally "dry" winter period and lower during the "wet" late spring and summer months. This redistribution of flow results in a flatter hydrograph with fewer and smaller flood peaks, and a shift in the occurrence of the high flows earlier in the hydrologic year (Fig. 3).

Furthermore, the variation of flood parameters (Table 7), as indicated by the coefficient of variation, is higher in the 2xCO_2 scenario than in present climate conditions. The higher variation of rainfall producing high flows which is the second flood producing mechanism in the altered climate scenario, and the variation of the flow from the ripe and transient snowpacks may explain the higher variation of the flood parameters.

Comparison of the Flood Response of the two Study Watersheds to Climate Change

Hydrologic simulation results indicate significant differences in the flood response of the two study watersheds. In the Upper Campbell watershed located at the Pacific Coast of British Columbia, the change in the global climate results in increases in the frequency, magnitude, volume, and duration of floods. In the interior mountain Illecillewaet basin the floods would be expected to reduce in frequency, magnitude, and volume. In the maritime basin of Upper Campbell River, a dramatic decrease of snowfall and snowpack accumulation, and a 43% increase in annual rainfall is expected. Rainfall runoff has a much higher hydrologic response than the snowmelt runoff. Therefore, there would be a significant increase in flood volume and magnitude.

On the other hand, in the Illecillewaet watershed the higher snowfalls at the higher elevations during the winter months compensates partly for the decrease of snowfall during the spring months but the snowpacks became more transient and start melting earlier in the year. Also, the increased rainfall at the lower elevations during the winter and spring months sustain higher flows in the traditionally "dry" winter period, in the case of altered climate. The overall result is that the flows would increase during the winter months and decrease during the late spring and summer months. The result is a flatter hydrograph in the Illecilewaet watershed. These changes affect the frequency, volume, and magnitude of flood flow and as well as the timing of the flood flow which under the climate change scenario would occur earlier in the hydrologic year.

Conclusions

This study used the output of the CCC GCM and the U.B.C. watershed model to simulate the effects of climate change on the flood response of two watersheds. Changes not usually accounted for in other studies, have been considered. For example, in addition to the changes in precipitation and temperature, changes in the spatial distribution of precipitation, vegetation coverage and biomass production, plant physiology, cloud cover, and glaciers have been considered in the simulation. The hydrological simulation of the two study watersheds, both located in humid areas but at different geographical regions, respond differently under the climate change scenario.

For both basins the effect on evapotranspiration is small because the increased biomass production of the vegetation compensates the decreased evapotranspiration due to stomata closure. However, the annual snowmelt dominated runoff of the interior Illecillewaet watershed is affected more, because of the precipitation and temperature changes, and increases by 21% as compared to a 7.4% increase for the rain dominated runoff of the maritime Upper Campbell basin. The increase of the mean annual runoff of the Illecillewaet watershed is distributed over the winter months changing the shape of the streamflow hydrograph and decreasing the magnitude, volume, and frequency of the flood flow, which historically occurs in summer. On the other hand, although the runoff increase in the Upper Campbell watershed is concentrated in the winter months, it does not affect the time distribution of flow but increases the magnitude, the volume, the duration, and the frequency of the flood flow. These conclusions are very important for both study watersheds because both basins supply water to reservoirs used for hydroelectric power generation, water supply, and flood protection. The change in the flood response of the watersheds under the climate change scenario will affect the reservoir regulation and operation.

In interpreting the results presented above, it is important to examine the assumptions that were made. Firstly, the key assumption is that the present and altered climate scenarios were identical except that the monthly precipitation and temperatures were adjusted by factors derived from the outputs of CCC GCM simulation scenarios for $1xCO_2$ and $2xCO_2$. This assumption adjusted only the mean monthly values but it leaves the standard deviation of precipitation and temperature unaffected. This procedure preserves the historical variability and may not be representative for an altered climate. In addition the precipitation arrival processes, the sequence of dry-wet days, remained unchanged under the altered climate scenario.

A key point of the climate change simulation is that the CCC GCM is a steady state model so that it generates data at constant CO_2 concentration and does not simulate the effects of CO_2 changing gradually from the present conditions to higher concentrations. The result is that other feedback mechanisms that are not accounted for may develop and cancel out the effects of global warming, and also the biosphere may react in a different way to the gradual changes as compared to the abrupt change from one scenario to another.

The present work is based on assumptions derived from present knowledge and research, as cited in the paper. Further research is needed to understand the response of climate in increased CO_2 atmospheric concentrations, study the meteorological parameters that affect the climate change, investigate the feedback mechanisms that may develop, and improve the prediction, and spatial scale of GCMs, especially for mountainous regions.

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