IMPACT OF CLIMATE CHANGE ON STREAMFLOW IN THE UPPER YUKON RIVER NEAR WHITEHORSE

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ABSTRACT

The upper Yukon River system provides flow for the operation of the hydroelectric plant at Whitehorse. Marsh Lake acts as a storage reservoir for the system during the low flow winter months and has also historically experienced flooding in the late summer when it is in an uncontrolled state. It is desirable to assess the impacts of the projected climate change on the streamflow of the upper Yukon River system for hydroelectric and flood mitigative purposes. Multiple regression relationships were developed between monthly Marsh Lake inflows and climatological parameters for Whitehorse. Using this relationship with projected temperature and precipitation increases generated by the Canadian Climate Centre GCM, monthly inflows to the system were developed for a "post climate change" scenario of a 100 percent increase in carbon dioxide in the atmosphere. For comparison purposes, a classical water balance was carried out. Evapotranspiration rates were estimated using the complementary relationship areal evapotranspiration methodology.

INTRODUCTION

The upper Yukon River system provides flow for the operation of the hydroelectric plant at Whitehorse. Marsh Lake acts as a storage reservoir for the system during the low flow winter months and has also historically experienced flooding in the late summer when it is in an uncontrolled state. It is desirable to assess the impacts of the projected climate change on the streamflow of the upper Yukon River system for hydroelectric and flood mitigative purposes.

Multiple regression relationships were developed between monthly Marsh Lake inflows and climatological parameters for Whitehorse. Using this relationship with projected temperature and precipitation increases generated by the Canadian Climate Centre GCM, monthly inflows to the system were developed for a "post climate change" scenario of a 100 percent increase in carbon dioxide in the atmosphere.

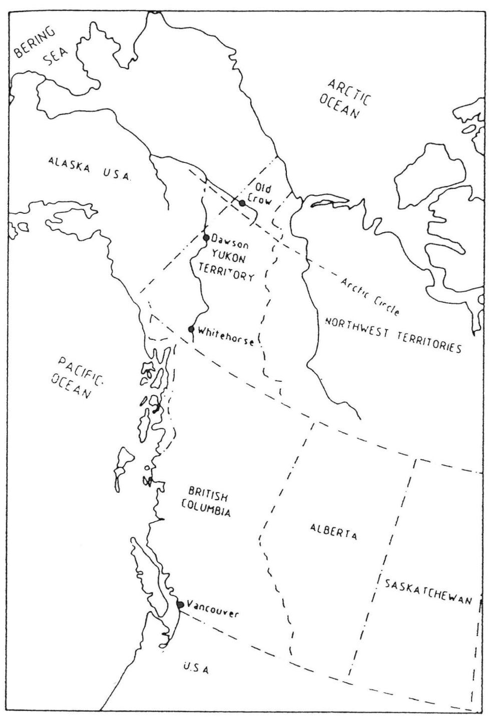
For comparison purposes, a classical water balance was carried out. Evapotranspiration rates were estimated using the complementary relationship areal evapotranspiration methodology developed by Morton (1983).

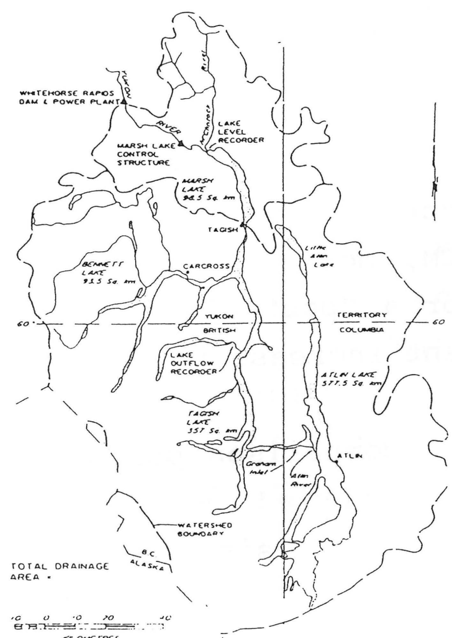
SETTING

The Yukon River originates in the glacier fields of the Coast Mountains of British Columbia and flows 2900 kilometres through Yukon Territory and the State of Alaska to the Bering Sea (figure 1). The

19,400 km^2 upper Yukon River above Whitehorse, lies within the Yukon Cordilleran physiographic region. The eastern portion of the basin consists of rolling uplands and low lying mountains, while the western portion consists of the rugged, high elevation Coast Mountains. Elevations range from 700 to 1500 metres in the east to 2400 metres in the rugged mountainous portion in the west. The upper Yukon River contains an extensive series of lakes which provide a significant amount of natural storage (figure 2).

Fig 1: Location Map   Fig 2: Upper Yukon R System





The system is controlled artificially during the winter months by the Marsh Lake control structure which transforms much of the lake system into a storage reservoir for the hydroelectric plant at Whitehorse. The basin is within the Boreal forest subregion which is characterized by spruce, pine and poplar in the lower elevations and some alpine fir at higher elevations, with tundra above treeline which lies at approximately 1500 metres (Oswald and Senyk, 1977). The basin lies within the discontinuous/scattered permafrost zone with sporadic permafrost at higher elevations.

Most of the basin has a subarctic continental climate which is characterized by a large annual variation in temperature, low relative humidity and relatively low precipitation. The western icefield border region is an exception with a transitional climate ranging from a wet maritime climate on the windward slopes to a dry continental climate on the leeward side of the Coast Mountains (Wahl et al, 1987). Mean annual temperatures range from $-1^{\circ}c$ on the leeward side of the mountains to $-4^{\circ}c$ in the icefield areas. July is the warmest month with monthly mean temperatures of 10 to $15^{\circ}c$. January is the coldest month with monthly mean temperatures of -10 to $-25^{\circ}c$. Precipitation throughout much of the basin is generally low with values of 200 to 300 mm. The western icefield area receives up to 1000 mm annually.

The mean annual flow of the upper Yukon River as represented by the Yukon River at Whitehorse is 242 m^3/s. A short distance downstream of Marsh Lake, flows at Whitehorse are well represented by Marsh Lake outflows. Peak flows generally occur in the late summer in response to glacier and high elevation snowfield melt contributions (the Marsh Lake control structure is fully open between May 15 and September 15 hence the upper Yukon system is in an unregulated mode during this period). Lower elevation snowmelt generates relatively high flows during the early summer and because of the storage induced lag, streamflow discharge remains high through the fall. The mean maximum monthly discharge and mean annual maximum instantaneous discharge are 493 and 521 m^3/s respectively. Minimum flows are regulated for hydroelectric operation purposes. The mean minimum monthly discharge of 148 m^3/s occurs in April. This value is approximately 210 percent of the unregulated value.

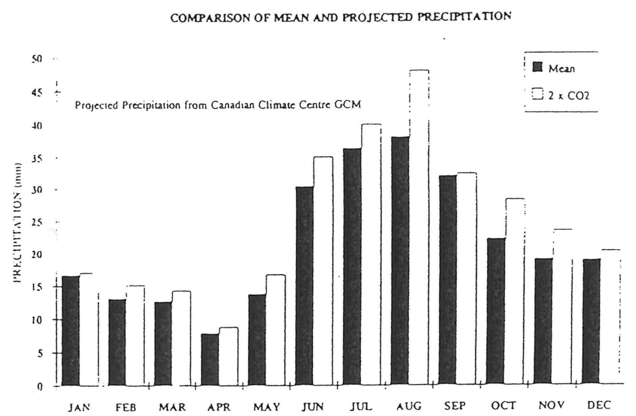
For study purposes the inflows to Marsh Lake were calculated using the equation of continuity with measured downstream discharge and lake stage. This procedure removes the winter storage influence provided by the Marsh Lake control structure and provides an accurate estimate of available water for power generation.

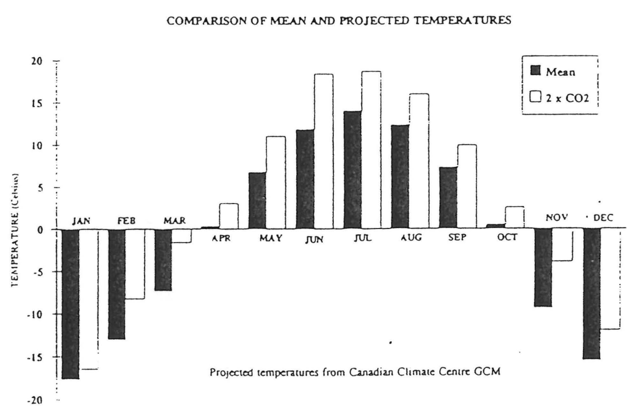
CLIMATOLOGICAL DATA BASE

The available climatological database for the upper Yukon River basin was inspected for its suitability for used in the project. Climatic data is available for several communities, however, due to the significant amount of missing data and lack of a solar radiation data or an index thereof, only Whitehorse records were found suitable for use.

Simulated monthly temperature and precipitation data based on the projected climate change scenario of a 100 percent increase of CO_2 in the atmosphere were provided by the Canadian Climate Centre and are based on a global circulation model (GCM) developed by the Centre in 1988 (figure 3). This

Figure 3: Comparison of Mean and Projected Precipitation and Temperature





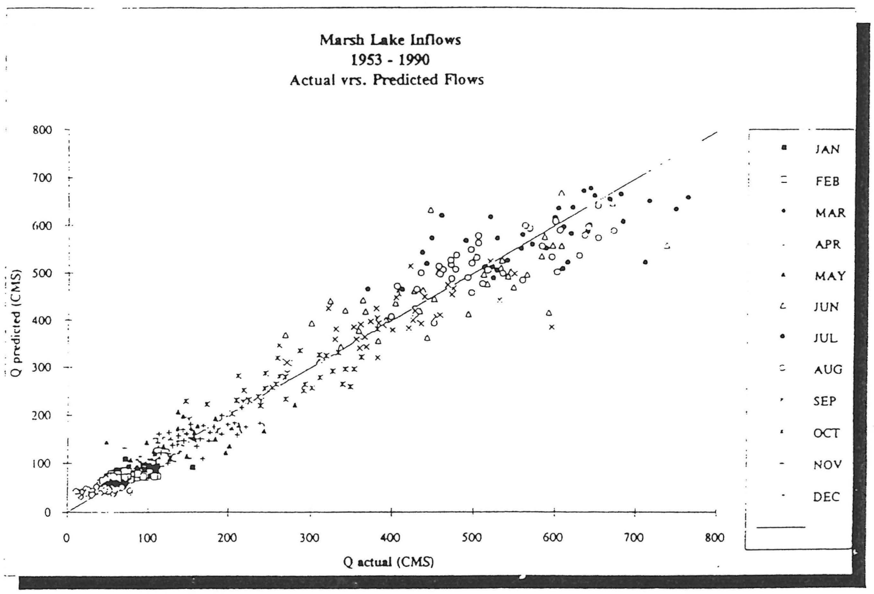
information was used as a starting point and was not evaluated or discussed in detail.

STREAMFLOW ESTIMATION

Multiple regression relationships were developed between temperature and precipitation parameters for Whitehorse, and calculated inflows to Marsh Lake. These relationships were than used to derive a post climate change hydrograph for the system (Janowicz and Ford, 1994).

Developed relationships for late spring and summer flows are relatively good while winter flows were more difficult to predict (figure 4). The weakest

Figure 4: Marsh Lake Inflows - Actual vs Predicted

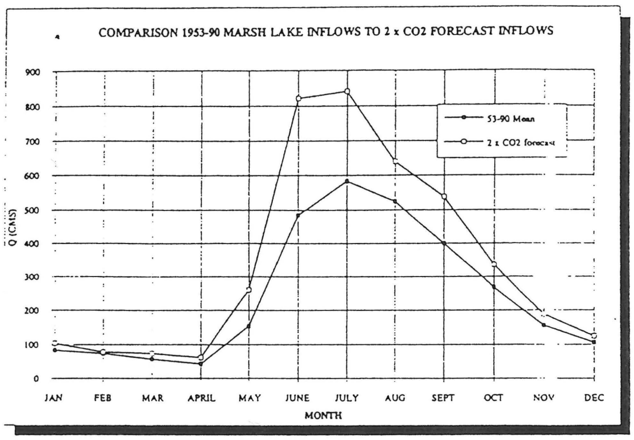


relationship is for April which is the month of the lowest annual flows.

The most significant independent parameter for late spring and summer high flows was found to be monthly mean temperature for the month of the flow being estimated. Other parameters which were utilized included cumulative winter and summer temperature and precipitation, and various combinations of monthly values. There were no dominant independent variables for winter low flow periods.

Projected values of temperature and precipitation based a 100 percent increase in atmospheric carbon dioxide were used to develop the post climate change hydrograph (figure 5).

Figure 5: Mean and Projected Marsh Lake Inflows



WATER BALANCE

Reasonable flow projections are provided by the regression analyses technique when used with climatological data within the historical range of observed values. Once outside the historical range, there is more uncertainty associated with the projections because of potentially unaccounted feedbacks. The historical and projected mean annual temperatures for Whitehorse are -0.9 and 3.0^{0}C respectively, as compared to the historical maximum of 1.2^{0}C. The historical and projected mean annual precipitation for Whitehorse are 263 and 299 mm respectively, while actual observed values exceed 300 mm on numerous occasions.

For comparison purposes, a version of the basic water balance was used to provide an independent estimate of mean annual runoff:

$$R = P - E - S$$

where R is runoff, P is precipitation, E is evapotranspiration and S is basin storage. For simplicity purposes, it is assumed that the change in basin storage equalizes in the long term and can be eliminated from the equation yielding:

$$R = P - E.$$

As with the earlier component of the study, historical streamflow data were used to calculate annual inflows into Marsh Lake and these were converted to runoff over the basin.

Basin precipitation as represented by the available data is thought to be a potentially significant source of error in the water balance. It is obvious that an underestimation problem exists since recorded runoff is consistently greater than the corresponding precipitation. To develop a positive water balance it was necessary to adjust the historical precipitation data. A value of 2.3, the mean of the available historical data, was used as an adjustment factor.

EVAPOTRANSPIRATION

Evapotranspiration for the basin was estimated using a computer model developed by Morton (Morton et al., 1985):

$$E_a = 2E_w - E_p$$

where E_a is the areal or actual evapotranspiration, E_w is the evapotranspiration that would occur under saturated conditions, and E_p is the potential evapotranspiration. E_p is calculated using energy and vapor transfer equations using a variation of the Penman equation (1948) where a vapor pressure coefficient is used instead of a wind function. Morton's complementary relationship areal evapotranspiration (CRAE) is based on the theory that there is an inverse relationship between potential evapotranspiration and water availability for areal evapotranspiration. The theory is based on the concept that when evaporation occurs from a saturated area, reducing areal evaporation, the energy released will than increase potential evaporation (Granger and Gray, 1989). Thus there exists a complementary relationship in which potential evapotranspiration is a effect of, rather than a cause of evapotranspiration. The complementary relationship is based on responses of the energy balance to changes in surface wetness, unlike other methods which rely on correlations between actual and potential evapotranspiration. Morton suggests that the potential evapotranspiration is at a maximum in a dry environment where actual evapotranspiration is zero. As water supply increases so does actual evapotranspiration which in turn cools and drys the overlying air mass causing potential evapotranspiration to decrease. Actual and potential evapotranspiration converge at a point, the wet environment evapotranspiration rate, which Morton calculates as one half of the dry environment potential evapotranspiration rate.

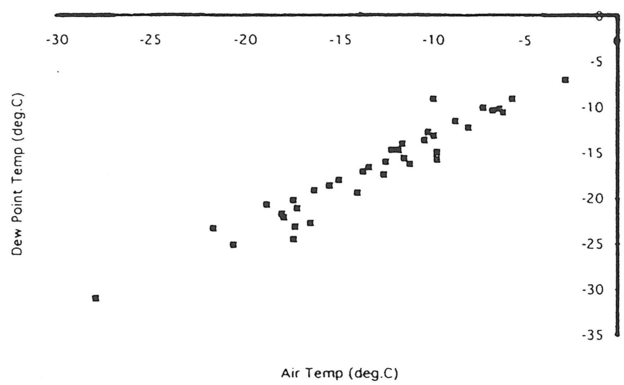
The computer model estimates areal evapotranspiration using readily available temperature, humidity and sunshine duration data. This procedure eliminates the need to consider soil-plant interactions, or to derive regional coefficients.

Required input data include air temperature, humidity which may be in the form of relative humidity, vapour pressure or dewpoint temperature, and, an insolation parameter, which may be in the form of observed global radiation, observed sunshine duration or the ratio of observed to maximum sunshine duration. Dewpoint temperature and observed sunshine duration with air temperature, were used in the present study. The model also requires annual precipitation and station altitude and coordinate location to calculate the necessary energy balance functions.

For the purpose of estimating "post climate change" evapotranspiration, functional linear relationships were developed between monthly air temperatures at Whitehorse and dewpoint temperature, and, monthly precipitation and sunshine hours.

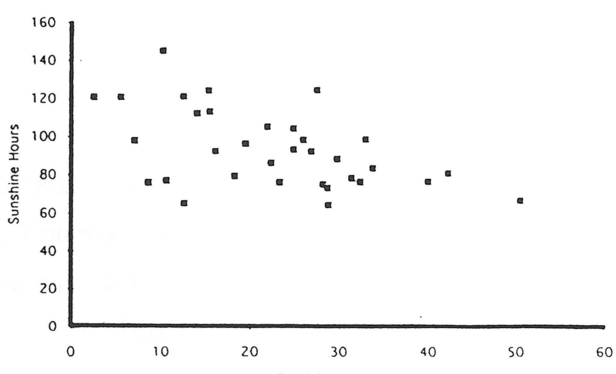
Useable relationships were developed for estimating dewpoint temperature and sunshine hours. Good results were obtained between air temperature and dewpoint temperature especially for the winter months (figure 6). The relationship between precipitation

Figure 6: February Whitehorse Air Temperature/Dew Point



and sunshine hours is not as good, but obvious trends are apparent (figure 7). Best results are

Figure 7: October Whitehorse Precipitation/ Sunshine Hours



obtained for the summer high precipitation months.

Evapotranspiration estimates were made for the Upper Yukon system using Whitehorse climatological information (table 1). The input parameters were

Table 1: Mean and Projected Data

MEAN MONTHLY DATA 1953-90

	Temp (°C)	Precip (mm)	Dew Point Temp (°C)	Sunshine (Hrs)	Net Rad (MJ/m^2)	Evapotranspiration Potential (mm)	Evapotranspiration Actual (mm)
Jan	-18.8	16.7	-19.4	46	-30.5	-6.5	-6.5
Feb	-13.1	13.2	-16.7	96	-33.5	-2.0	-2.0
Mar	-7.4	12.8	-12.7	160	5.9	14.5	14.5
Apr	0.3	7.9	-7.3	233	63.5	76.0	19.8
May	6.8	13.9	-2.8	263	102.7	131.4	32.0
June	11.9	30.5	2.1	270	115.6	159.9	42.5
July	14.1	36.4	5.6	254	104.5	156.4	41.8
Aug	12.4	38.2	5.0	232	72.1	122.3	23.6
Sept	7.3	32.2	1.3	139	12.8	42.3	13.6
Oct	0.5	22.4	-4.1	93	-23.9	11.4	7.7
Nov	-9.4	19.2	-12.4	47	-30.1	-2.2	-2.2
Dec	-15.6	19.1	-17.0	25	-31.3	-5.7	-5.7
Mean/Annual	-0.9	262	-6.5	1858	327.8	697.8	179.1
2 X CO_2 PROJECTED DATA							
Jan	-17.6	17	-19.5	47	-31.2	-4.4	-4.4
Feb	-8.3	15	-12.0	92	-33.4	-1.5	-1.5
Mar	-1.6	14	-8.1	158	4.3	22.8	14.2
Apr	3.0	9	-5.5	231	65.0	88.3	17.2
May	11.0	17	0.34	260	104.2	159.5	26.1
June	18.4	35	6.0	264	113.7	213.0	23.8
July	18.7	40	7.3	254	105.3	205.6	21.4
Aug	16.0	48	6.5	229	74.2	152.6	13.7
Sept	9.9	33	3.1	141	15.1	52.1	11.8
Oct	2.5	28	-2.6	87	-24.9	14.0	4.8
Nov	-3.4	24	-6.5	45	-27.5	0.3	0.3
Dec	-12.0	20	-14.2	25	-32.4	-4.5	-4.5
Mean/Annual	3.1	299	-3.8	1833	332.5	897.6	122.8

adjusted using the provided temperature and precipitation projections and adjusted dewpoint temperatures and hours of sunshine. Provided monthly temperature and precipitation values indicate a three fold increase in mean annual temperature and a 14 percent increase in mean annual precipitation. Dewpoint temperature is expected to increase by close to a factor of two, and sunshine hours are expected to decrease slightly. Estimated post climate change impacts in potential and actual evapotranspiration rates indicate 29 and 30 percent increases and decreases will occur respectively.

The greatest change is expected to occur during the summer months when actual evapotranspiration rates are projected to be about half of current rates.

Given the assumptions and extended climatological data, the projected trend in decreasing actual evapotranspiration seems reasonable. Greater cloud cover can be expected with the increase in precipitation. This will result in a decrease in incident global radiation while increasing air temperatures. Though the increased precipitation and cloud cover would be expected to produce more humid conditions, this impact is overridden by the very significant monthly temperature increases which result in a vapor pressure deficit and subsequent decrease in relative humidity. While there is a slight increase in net radiation as a result of the decreased relative humidity, areal evapotranspiration rates are expected to decrease. Of potential sources of error, perhaps the greatest is associated with the soil heat flux and its impact on net radiation, which is not considered by the model (Granger, 1994). Estimates of net radiation may be off by 5 to 8 percent during the summer when the soil is thawed, and as much as 20 percent during the early spring.

A sensitivity analysis using projected 2 X CO_2 input parameters indicates that temperature is the dominant variable. Consecutive evapotranspiration estimates were made using historical mean data with the addition of individual "post climate change" parameters of air temperature, dew point temperature, sunshine hours and precipitation in turn yielding projected values of actual evapotranspiration which were 36, 155, 99, and 112 percent of the historical mean data respectively. These results are supported by a more rigorous sensitivity analysis carried out by Granger and Gray (1989). Kite (1993) obtained a similar trend using the complementary relationship areal model for the Kootany basin in similarly mountainous area of British Columbia. Kite suggests that evapotranspiration rates may be further decreased by 25 percent as a direct effect of increased CO_2 on plant physiology based on work by Allen (1990) who suggests that CO_2 enrichment would decrease stomatal conductance and subsequent transpiration rates. Haas and Marta (1988) obtained a similar trend using the complementary relationship areal model for the Lake Diefenbaker area of Saskatchewan with increased temperature and humidity data, decreased insolation data, and unchanged precipitation as compared to the historical. Similarly Rouse and Boudreau (1993) suggest that under some vegetation conditions evapotranspiration rates would decrease due to reducing incident radiation to the ground surface.

Others suggest that evapotranspiration will increase due to a increase in available energy. Ripley (1987) suggests that evapotranspiration rates in northern Canada will increase by 12 percent. Hinzman and Kane's (1993) work in Alaska shows that evapotranspiration is likely to increase with increasing temperature and precipitation and will decrease with an increased temperature and reduced precipitation scenario.

DISCUSSION

Multiple regression relationships were developed between monthly Marsh Lake inflows and climatological parameters for Whitehorse. Reasonable relationships were obtained for most months though results were better for the open water season. Using this relationship with projected temperature and precipitation increases generated by the Canadian Climate Centre GCM, monthly inflows to the system were developed for a "post:climate change" scenario of a 100 percent increase in carbon dioxide in the atmosphere.

A classical water balance was carried out for comparative purposes. This study component indicated that annual rates of actual evapotranspiration would decrease by 30 percent yielding calculated mean annual runoff value of 535 mm for the "post climate change" scenario as compared to 564 mm generated by the regression method. These values represent 134 and 141 percent increases respectively.

The study area is within an extremely sensitive ecoregion in terms of atmospheric feedbacks. Consequently it is difficult to fully account for the magnitude of the feedbacks leading to potentially unaccounted sources of error associated with energy balance assumptions. Potential changes to the physical environment which will affect energy and water balance processes could be significant. The study area contains scattered permafrost which will likely melt entirely or result in a thickened active layer, altering surface runoff and groundwater interactions. According to Kane et al (1991) the discontinuous permafrost boundary could be shifted 100's of kilometres northward eliminating 50 percent of permafrost within this zone.

The impact on the significant glacierized areas is less certain. The common assumption is that global warming will increase melt; however due to atmospheric feedback processes, especially precipitation, this may not be the case (Adams, 1992). Additional cloud cover may limit available energy to the snow surface. Additional snow, in addition to contributing to ice growth above the firn line, may increase albedo, thereby reducing available energy. The additional snow will also utilize significant energy for the snowmelt process, while diverting this energy from potential glacier melt processes.

Vegetation patterns will change, altering rates of interception, snowpack accumulation, ablation and melt, and evapotranspiration. It is difficult to project the magnitude of this change though it is probably a valid assumption that there will be a northward migration of higher order plant species. Perhaps the greater impact will be associated with the increase in treeline elevation and the migration of higher order species to higher elevations. Edlund (1992) suggests that such changes may take centuries due to the need for a sufficiently developed soil profile.

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