MACROSCALE HYDROLOGICAL MODELLING WITH GCM CLIMATE DATA

by

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ABSTRACT

General circulation models (GCMs) perform vertical water and energy balances at 20 or 30 minute time intervals for grid points 2-4° apart but generally contain no information on the land-phase transfer of water between grid points or within watersheds. This study used a distributed hydrological model with data output from the Canadian Climate Centre's GCM. A water balance was carried out at 12-hour time intervals for a 10-year period using GCM grid points in and surrounding the 1.6 million km^2 Mackenzie River Basin in north-western Canada. The water surpluses from each grid point were accumulated to provide a simulated hydrograph at the outlet of the Mackenzie Basin. The hydrological model was calibrated and verified using five years of recorded climatological and hydrometric data as well as land cover data from NOAA AVHRR images. The climatological outputs from the GCM were then used as inputs to the hydrological model, generating a further hydrograph for the Mackenzie River. It was found that, by itself, the GCM overestimates water excess or runoff within the basin and that using a hydrological model with the GCM climatology produces a better representation of the recorded flow regime. The method allows verification of a GCM performance.

INTRODUCTION

Atmospheric general circulation models (GCMs) are tools derived from numerical weather prediction models. They are based on the physical laws of conservation of energy and mass for a rotating sphere subject to an external heat source and are used to simulate the behaviour of the atmosphere over long periods of time. These models include descriptions of both large-scale atmospheric processes and smaller-scale processes such as cloud distribution, precipitation generation, surface transfers of energy, moisture and momentum and land surface hydrology (Boer et al., 1984). The models operate at time intervals of about 20 minutes and at resolutions in the order of 2 to 4 degrees latitude and longitude.

While the atmospheric components of the GCMs are often very sophisticated (dividing the atmosphere into many layers) and the land-phase components may be very detailed, Henderson-Sellers and Pitman (1993) have shown that the land-phase parameterizations in current GCMs do not agree on predictions of energy fluxes, snow depth or water excesses, even when all atmospheric forcings are identical.

From a hydrological point of view, another, more serious, problem with GCMs is that they contain no lateral transfer of water within the land-phase. GCMs carry out a vertical water balance at each grid point at each time interval using precipitation, evapotranspiration, snowpack and groundwater storages. However, any "water excess" or runoff is discarded and plays no further role in the model computations, so that even if the GCMs were able to simulate water excess correctly, they would still be operating with an incomplete hydrological cycle. From the climatologists' viewpoint this loss of information may not be significant but, if the data from GCMs are to be used to investigate the effects of possible climatic change, then this shortcoming becomes very important. The political impetus for climatic change studies is that such changes may affect our own lifestyle and our lifestyle depends, to a large extent, on the lateral distribution of water.

In the first phase of this study, runoff was derived for the Mackenzie River Basin (Figure 1) by accumulating water excesses from water balances of the Canadian Climate Centre GCM II (CCC GCM II) CCC (1991) at appropriate grid points. The second phase calibrated and verified the SLURP distributed watershed model using five years of recorded climatological and hydrometric data for the Mackenzie Basin. The third phase used the climatological outputs from the CCC GCM II as distributed inputs to SLURP. The hydrographs and water balances derived directly from the GCM were compared with those from the SLURP model and with the observed data. The Mackenzie Basin was chosen both because of its large size (1.6 x 10^{6}km^2) and because it is the site of many studies in the Canadian contribution to the GEWEX project (Krauss, 1992).

GENERATING A HYDROGRAPH DIRECTLY FROM THE GCM

The CCC GCM II operates on a transform grid of 3.75° x 3.75° and a twenty minute time

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interval. The land-surface component of the model assigns two vegetation types out of twenty-one to each grid point. Each vegetation type has a soil depth, a snow masking depth and an evapotranspiration factor associated with it. Surface and soil temperatures are tracked using heat storage and heat transfer to and from the atmosphere with thermal conductivities defined as functions of soil type, moisture content and snow cover. Water budgets are maintained for liquid and frozen soil water and for snow pack. Maximum water holding capacities are calculated from soil depths and porosities.

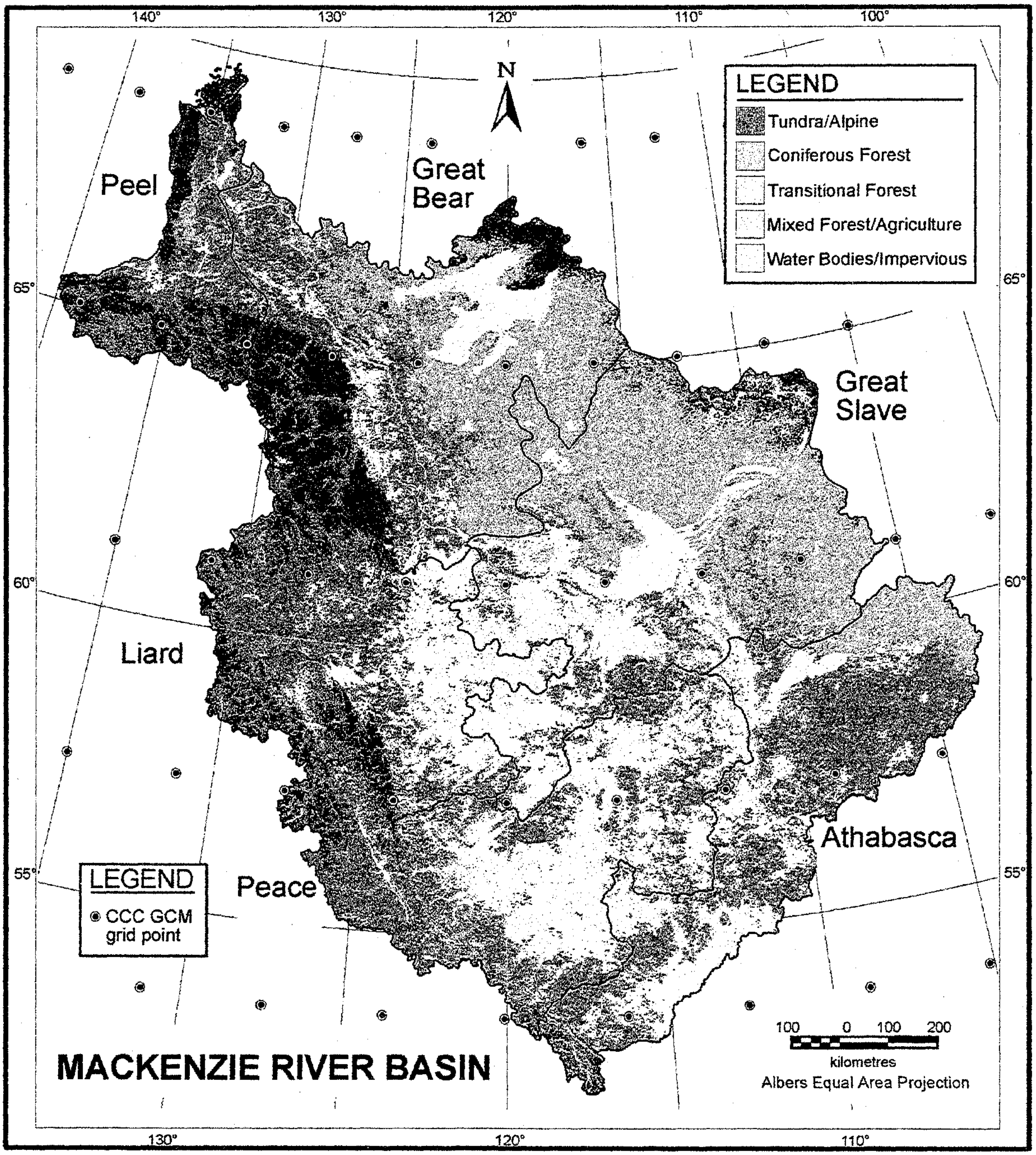

Figure 1 Mackenzie River Basin showing CCC GCM II grid points and areas surrounding grid points.

A data set has been published (CCC, 1991) containing 21 fields accumulated or sampled at 12-hour time intervals over a 10-year period for each of two model runs of the CCC GCM II (one with current CO_2 levels, one with doubled CO_2). The data set contains values of each field at each time on a grid of 30 equally spaced longitude points and 19 Gaussian latitudes for a North American window. The water excess, R, was computed from a vertical water balance at each grid point at each 12-hourly time interval:

$$R = PCP - QFS - \delta(SNO+WFA+WFL) \qquad (1)$$

where PCP and QFS are the precipitation and evaporation and $\delta(SNO+WFA+WFL)$ is the change in the masses of snowpack (SNO), frozen soil moisture (WFA) and liquid soil moisture (WFL), all in kg/m^2. It was found that for any particular 12-hour period the water excess could be positive or negative but, fortunately, when the 12-hourly water excesses were accumulated to monthly means, they were all positive and conformed to an annual cycle.

The 12-hourly water excesses from each grid point over the entire Mackenzie Basin were then aggregated, using the individual areas of each grid square and the percentages of each grid square within the basin (Figure 1), into 10-year mean streamflows for each month. Figure 2 compares the resulting hydrograph (dotted line) with the long-term (1972-1990) monthly mean flows recorded by Water Survey of Canada (solid line) at station 10LC014, Mackenzie River at Arctic Red River, the most northerly station measuring the whole river (WSC, 1991). Figure 2 shows that the streamflow volumes generated from the CCC GCM II are much higher than those recorded and that the GCM peak flow occurs much earlier in the year.

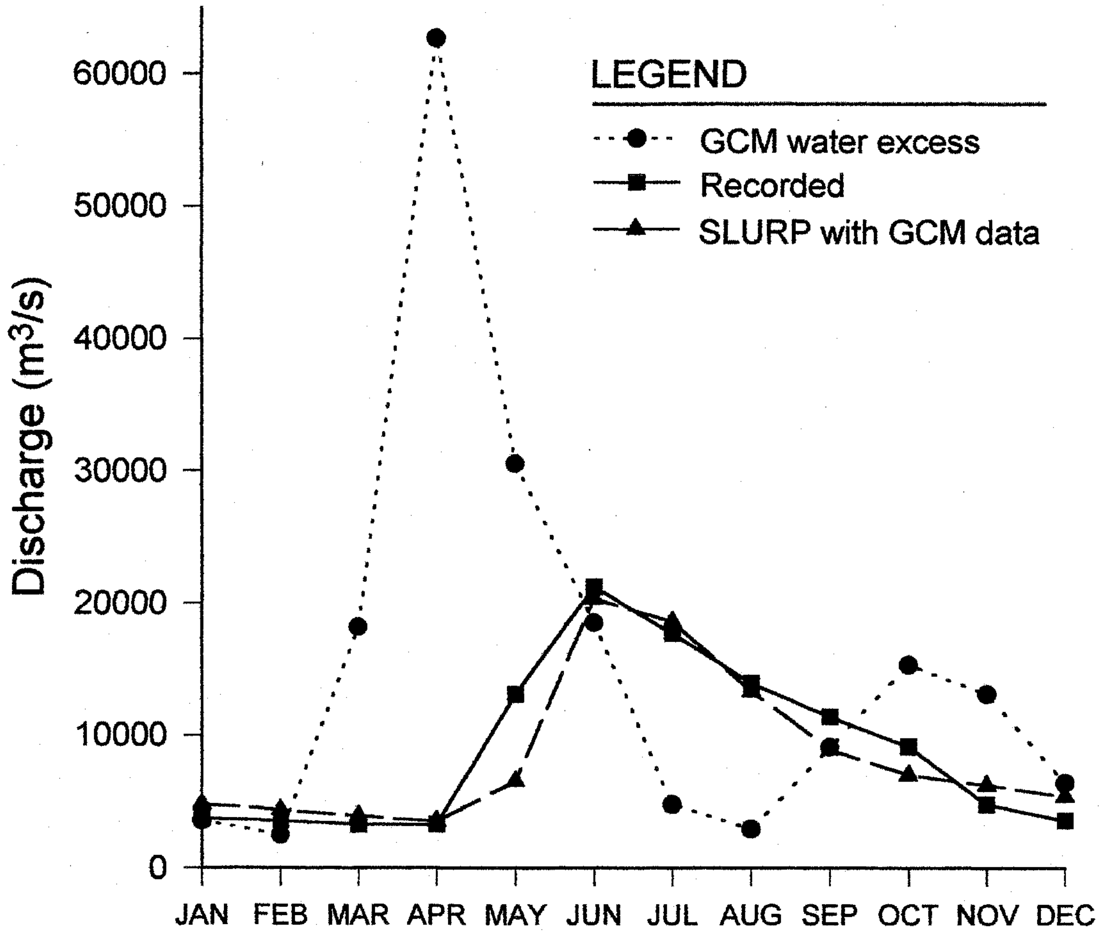

Figure 2 Comparison of long term (1972-1990) mean monthly streamflow at station 10LC014, Mackenzie River above Arctic Red River, (solid line) with mean monthly streamflow simulated from water excesses of CCC GCM II (dotted line), and mean monthly streamflow simulated by the SLURP hydrological model using distributed climatological data from the CCC GCM II for the ten year test period (dashed line), m^3/s.

Similar characteristics seem to occur with other GCMs. Figure 3 compares the hydrographs for the Mackenzie River derived from CCC GCM II water excesses with those from the GISS (Kuhl and Miller (1992) and the ECHAM (Arpe et al., 1992) models. The lack of lag and attenuation in the CCC and GISS hydrographs is due to the fact that these GCMs contain no land-phase transfer mechanisms and so delays and losses caused by slow groundwater flow, channel flow and lake storage are not modelled. ECHAM has a simple river runoff model which produces a lag but no attenuation.

CALIBRATING THE HYDROLOGICAL MODEL

The SLURP model

SLURP is a daily distributed hydrological model (Kite, 1993) in which the parameters are related to land cover (vegetation type). At each time increment, the model is applied sequentially to a matrix of Grouped Response Units (GRU) and land covers. A GRU is a watershed component made up of a number of computational units that may or may not be contiguous (Kite and Kouwen, 1992). A maximum of 50 GRUs and 10 land covers may be used, potentially dividing a watershed into 500 sub-units. Each application of the model (GRU x land cover) is represented by three non-linear reservoirs, one for snowpack, one for a rapid response (may be considered as a combined surface storage and top soil layer storage) and one for a slow response (may be considered as groundwater). The three reservoirs have specified initial contents; there is a maximum depression storage and a maximum allowable depth for slow storage.

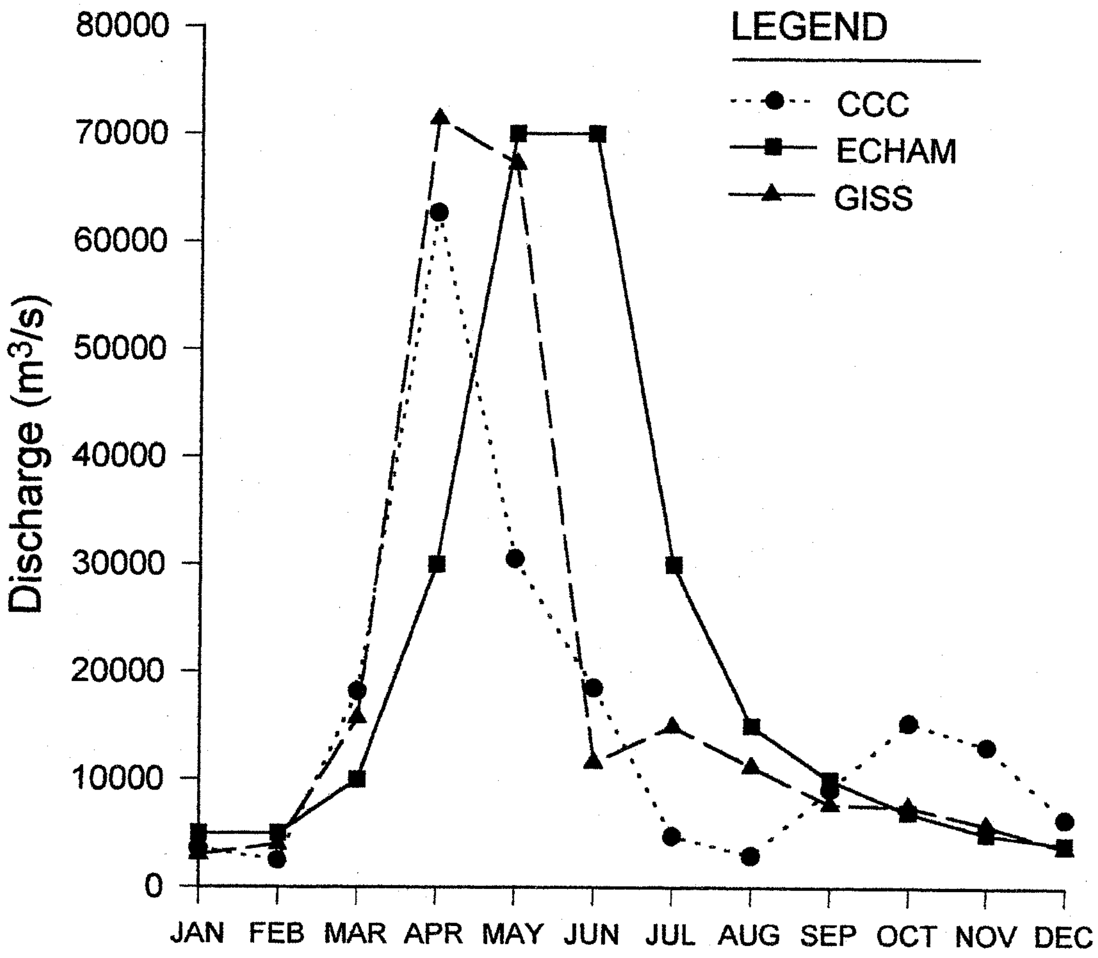

Figure 3 Comparison of mean monthly streamflows for the Mackenzie Basin simulated from the water excesses of CCC, GISS and ECHAM general circulation models.

Runoffs from each reservoir are accumulated from each land cover within a GRU using a travel time/contributing area relationship for each land class and the combined runoff is converted to streamflow and routed between GRUs. The travel times are derived using network analysis in a GIS. First, a digital drainage network was imported and the distances were computed from the outlet of the GRU to points at 25 km intervals along the stream network. Next, a 10 x 10 km sampling grid was laid over the basin and drainage distances were interpolated for each point along the network. For each pixel the GIS then related land cover to distance from the outlet of the GRU and produced a distribution of to-stream and in-stream distances for each land cover.

A GIS was used to calculate the changes in elevation between each pixel and the GRU outlet and an average velocity, V m/s, was computed for each land cover using Manning's equation with a coefficient of roughness for each land cover, n, assuming that the hydraulic radius, R, (equal to cross-sectional area divided by wetted perimeter) is unity for an infinitely wide shallow channel. The calculated velocities were then used to convert the distances to travel times for each land cover and each GRU.

After the runoffs from all the land covers within a GRU are combined into a GRU streamflow, this flow is routed from the GRU to the next GRU down the stream system. In the SLURP model this routing may be carried out using a simple hydrological procedure or by accessing, from within the program, a user-written routine specifying any set of routing or regulation rules. The latter option is necessary, for example, if the stream system includes reservoirs. For the Mackenzie Basin, since there are no reservoirs on the main river, the hydrological routing option was used.

Calibration

Before the SLURP hydrological model could be used with the CCC GCM II data, it had to be calibrated using recorded climatological and hydrometric data. The Mackenzie Basin was divided into five GRUs corresponding to the locations of Water Survey of Canada streamflow gauging stations WSC (1991) for the Peace, Athabasca, and Liard Rivers and for the main Mackenzie River downstream of the Great Slave Lake and downstream of the Great Bear Lake (see Figure 1).

A one kilometre resolution land cover dataset covering western and arctic Canada was obtained from the Manitoba Remote Sensing Centre (Pokrant and Palco, 1991). The data were derived from NOAA AVHRR satellite imagery which was corrected, calibrated, projected, classified and finally manually edited after review and verification. A GIS was used to extract the land cover data for the Mackenzie River Basin and to reduce the original 12 land cover types to five major land cover categories, based on the expected hydrologic similarity. The areas of each category within each GRU were measured using the area cross-tabulation functions within the GIS.

Daily mean precipitation and temperature data for the period January 1, 1986, to December 31, 1990, were computed for each GRU using Thiessen polygons with data from the five closest climatological stations. In the near future, distributed precipitation data may be available from physically-based climatological models but, in the meantime, Thiessen polygons are the only available substitute. Daily areal evapotranspirations were computed for each GRU with the CRAE model using measured screen temperature, dew-point temperature and hours of bright sunshine. Daily streamflows at the outlets of each GRU were obtained for the same 5-year period from published Water Survey of Canada records.

Apart from the effects of the Bennett dam on the Peace River, all flows in the Mackenzie Basin are natural. As the comparisons used in this study are of long-term mean flows for the entire basin, the effects of the dam may be safely ignored. Similarly, although ice jams are an important feature of this northward-flowing river system, the effects are local and are short-term (1-5 days). While the effects of ice jams may result in the daily streamflows generated by the SLURP model differing from the recorded data they will have no effect on the long-term monthly flows used for hydrograph comparison. The Mackenzie Basin contains two large lakes, the Great Slave and the Great Bear. The effects of these lakes in delaying and attenuating river flows is included in the model through the set of maximum and minimum contribution times and by the between-GRU channel routing.

The hydrological model was then applied to the 5 x 5 matrix of GRUs and land cover classes, calculating runoff from each land cover within each GRU, converting to streamflow for each GRU and routing the streamflow downstream from one GRU to the next. The simulated streamflows were compared to the observed streamflows and the parameters of the model were calibrated to provide the best least-squares fit. The calibration procedure first manually estimated parameters on the basis of experience in similar basins, then carried out a grid search of parameter values, and finally used a built-in hill-climbing optimization program (Kite & Kouwen, 1992).

The calibration results show a good fit for the model. The Nash/Sutcliffe criterion (Nash and Sutcliffe, 1970) has a value of 0.91 compared with a perfect fit value of 1.0 and the water volume over the two years is less than 2% in error. When the model is verified over the three years 1988-1990, using the same parameter set, the performance naturally decreases but the Nash/Sutcliffe statistic is still a respectable 0.79 and the error in volume is still just over 3%.

USING CCC GCM II OUTPUTS IN THE HYDROLOGICAL MODEL

Once the hydrological model had been calibrated for the Mackenzie Basin the next step in the study was to use the outputs from the GCM as distributed inputs to the hydrological model.

Daily precipitations and average temperatures for the 10-year GCM data period were computed for each of the five GRUs using data from surrounding GCM grid points with weights based on the areas of the grid squares within the GRUs. The CCC GCM II output data set was adjusted for the time difference between GMT and Mountain Standard Time and to include data for February 29 in leap years.

Following the normal SLURP procedure, daily evapotranspiration would be computed using the CRAE method. However, the published outputs from the CCC GCM II do not include the global radiation data needed in the CRAE procedure and so the published evaporation data from the GCM were used as daily maxima which the hydrological model tried to satisfy depending on water availability.

The calibrated hydrological model was then run for the five land cover types in each of the five GRUs for each day of the 10-year GCM data set. The resulting daily streamflow data for the 10-year period were averaged to mean monthly values.

RESULTS

The mean monthly streamflows generated by the hydrological model from GCM data are compared (dashed line) to the long-term mean monthly recorded data (solid line) and to the hydrograph derived directly from the GCM water excesses (dotted line) in Figure 2. The comparison shows the striking way in which the hydrological model has corrected the volume and phase deficiencies of the GCM water excess hydrograph. The volume is more accurate because the hydrological model's lateral transfers allow accumulation of soil moisture in lower areas for enhanced evapotranspiration. The phase correction occurs because over 95% of the flows generated by SLURP for the Mackenzie Basin are groundwater with its long, slow, response and because channel and lake storage are included in the hydrological model. The channel routing mechanisms in SLURP produce an additional phase shift of 2-3 days between each GRU and an attenuation of about 10% while maintaining water volumes.

The precipitation, evaporation and water excess (or runoff) recorded, computed from published CCC GCM II data and output by the SLURP hydrological model are summarized in Table 1.

Table 1

Summary of water balance components as recorded,
as computed from the CCC GCM II
and as computed by SLURP, mm/year over the Mackenzie Basin.

	Precipitation	Evaporation	Runoff or water excess
Recorded	394		171
CCC GCM II	779	507	294
SLURP	476	279	162

The recorded precipitation is the weighted mean from the 22 climatological stations for the period 1986-1990 (the calibration/verification period) and the recorded runoff is the long-term mean for the period 1972-1990. The GCM and the SLURP data are both for the 10-year GCM experiment. The GCM precipitation value is the average of all the 39 grid points using equal weights. The SLURP precipitation value is derived from the same GCM point data but uses different weights to derive GRU-averages; the GRU-averages are then multiplied by the same factor used with recorded precipitation in the calibration. Similarly, the GCM evaporation value is the simple average from all 39 grid points. The SLURP evaporation is the average generated by the watershed model using the GCM evaporation as a maximum to be satisfied, if possible, from water availability.

Given the uncertainties in the GCM outputs and the lack of knowledge of the effects of climate on vegetation and land cover, it seems unlikely that estimates of the effects of climatic change on water resources can be of any practical use at this time. However, as a demonstration of technique, the SLURP model was rerun for the Mackenzie Basin using 10 years of GCM 2 x CO_2 data with the best estimates of climatic zoning under 2 x CO_2 conditions (Zoltai, 1988). Figure 4 compares the resulting hydrograph with that produced under current (1 x CO_2) conditions. The higher temperature and precipitation of the doubled carbon dioxide scenario produce a higher peak flow earlier in the year.

The results show that the average annual precipitation generated by the CCC GCM II is almost twice that recorded for the Mackenzie Basin. Because there is no lateral transfer of surface or groundwater in the GCM, water tends to pond and produce unrealistically high evaporation in subsequent time steps. Despite the higher evaporation, the aggregated water excess from the CCC GCM II is still nearly twice the long-term mean recorded streamflow. This finding agrees well with the extremely large water excesses found by Kuhl and Miller (1992) for GISS GCM and by Arpe, Behr and Dumenil (1992) using the ECHAM GCM (Figure 3).

CONCLUSIONS

General circulation models simulate the atmospheric component of the global hydrological cycle. Although GCMs are increasingly being linked to oceanographic models they are still simulating an incomplete hydrological cycle because of their lack of lateral transfer of water in the land-phase. This omission precludes studies of the effects of climate on fresh water availability and distribution and of the effects of changing river flows on ocean circulations.

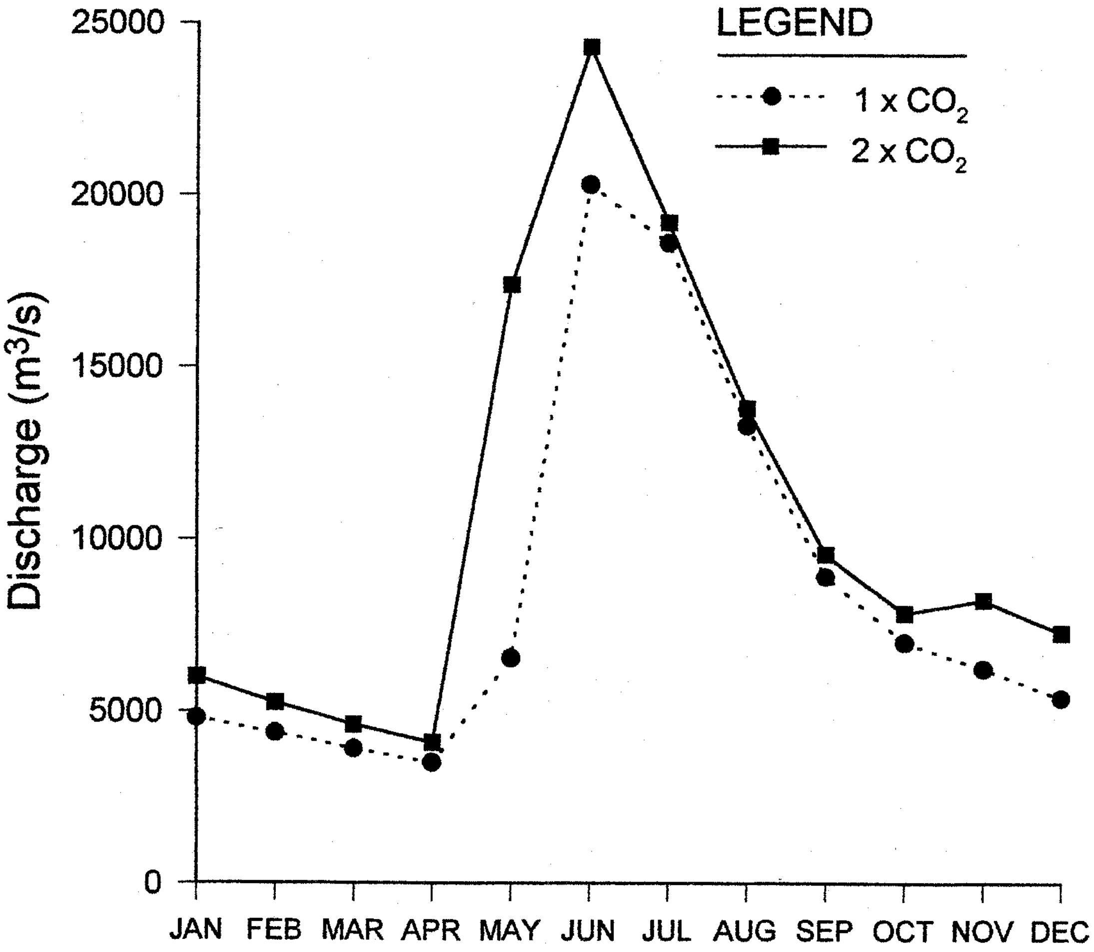

Figure 4 Comparison of mean monthly streamflows for the Mackenzie Basin generated by using the SLURP watershed model with 10 years of data from the CCC GCM II for 1 x CO_2 and 2 x CO_2 scenarios.

The major shortcoming in the GCMs is their lack of surface and groundwater routing mechanisms. Accumulations of the excess water from vertical water balances yield hydrographs that do not compare well with recorded data. Current GCMs often tend to overspecify some aspects of the hydrological cycle by having, for example, multiple soil layers (where no real data are available) while lacking such important features as within-grid variation in data fields and inter-grid transfers. This study found that water balances from published CCC GCM II data are inconsistent, often yielding negative "runoff" or water excess.

The SLURP hydrological model was calibrated and verified for the Mackenzie Basin using recorded hydrometeorological data. Data from the CCC GCM II were used as distributed inputs to the hydrological model and the resulting hydrograph was found to compare very well with the recorded streamflow. This result is a great improvement over using only the aggregated "water excesses" from the CCC GCM II and confirms the importance of having a realistic land phase model.

Although the present hydrological model improves the hydrology, it provides no feedback to the GCM and could not be used interactively in its present form. It is desirable to develop such interaction to avoid inconsistent water balances where, for example, the hydrological model removes water laterally from a GRU while the GCM removes the same water vertically by evapotranspiration.

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